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An Analysis of FM Jamming and Noise Quality Measures

THESIS

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Preface

This thesis was conceived to meet three primary objectives. The first was to explain the behavior of FM jamming, particularly in the case where the relationship between the bandwidth of the modulating noise and the bandwidth of the jamming barrage is such that the modulation could not be characterized as Wideband FM. The second was to critically consider (both theoretically and experimentally) three proposed methods of measuring noise quality in jamming scenarios and determine under what conditions they are valid and useful. The third was to design and demonstrate a valid technique for measuring the noise quality of operational jammers which could be implemented using commercially available equipment.

The first objective led to the development of terminology describing four possible types of FM-by-noise (FM/N) jamming based on the relationships that must exist between the three bandwidths involved: the bandwidth of the modulating noise, the bandwidth of the FM/N barrage, and the bandwidth of the victim receiver. The general characteristics of the noise produced in the victim receiver by each type of jamming are carefully considered with analyses of both the shape of the noise spectrum and the univariate probability density of the noise. The predicted characteristics of each type of jamming were experimentally validated using a simulated jammer and a simulated receiver.

The second objective led to the discovery of strengths and weaknesses in each of the noise quality measures proposed to date. Only the two noise quality measures which measured noise at the output of a victim receiver were considered in depth because the effectiveness of a given jammer is highly dependent upon the system it is trying to jam. Of these two, one was found to be inadequate under certain specialized conditions, and the other was found to be generally theoretically adequate, given some obvious modifications which were made.

The third objective led to the design of a set-up consisting of a digital oscilloscope, a PC controller and a set of programs written in C and Matlab, which were used to measure the noise

quality of an operational jammer in the sponsor's laboratory. It is believed that the ability of the sponsor to make noise quality measurements of operational jammers has finally been restored.

In all this work I owe much to the members of my thesis committee. Dr. Vital Pyati provided direction and the necessary technical background. Mr Eugene Sikora put together the necessary components for measuring noise quality on the commercial jammer. Major Mark Mehalic helped overcome initial difficulties with the laboratory equipment, and Capt. Joseph Sacchini gave me the idea that was central to the improvement of one of the noise quality measures. Additionally, I am indebted to Mr. Marvin Potts for his aid in programming, and to Capt. Charles Daly for his insights, support and the invaluable work which he did in this area previously. Lastly, I thank my wife, Christa, and my children for their sacrifices and encouragement.

Timothy Nathan Taylor

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Abstract

This thesis attempts to address three related problems. The first is to provide a complete description of the operation and characteristics of FM-by-noise (FM/N) jamming both at RF and at the output of the radar receiver, in terms of spectrum, time domain waveforms and univariate probability density. Particular emphasis is give to the case where the peak frequency deviation of the FM modulator is on about the same order as the bandwidth of the modulating signal since this case has been largely neglected previously. The second problem has to do with measuring noise quality in a jamming scenario. Noise quality measures which have been used in the past are analyzed theoretically and experimentally. The third problem has to do with designing a technique for making practical noise quality measurements on operational jammers.

The first problem is addressed by considering four cases: Wideband FM by wide frequency noise (WBFM/WFN), Wideband FM by low frequency noise (WBFM/LFN), Narrowband FM by wide frequency noise (NBFM/WFN), and Narrowband FM by low frequency noise (NBFM/LFN). The characteristics of these four cases are explored theoretically, and experimental results demonstrating each of the cases are presented.

The second problem is addressed by suggesting a new measure of noise quality at IF based on two measures. The gausianity of a noise signal is measured by forming a histogram of the amplitudes of uncorrelated samples as suggested previously, and, in addition to this, the whitness of the signal is measured by taking the FFT of correlated samples of a waveform, dividing point-by-point by the discrete frequency transfer function of the IF filter, and comparing the result to a flat spectrum.

The third problem is addressed by the development of a hardware and software setup which has measured the noise quality of an operational noise jammer. The hardware used is described here, and the software is included with a brief description.

The theoretical and experimental analysis of NBFM/N lead to the conclusion that a measure of noise quality which incorporates both the spectral whiteness as well as the gaussianity of the probability density function of a jamming signal should be adopted. A noise quality measure which does this is presented here. Also, it is recommended that the setup which was designed to measure operational jammers be used.

An Analysis of FM Jamming and Noise Quality Measures

I. Introduction

The work outlined in this thesis is the result of ongoing research to better understand FM-by-noise (FM/N), a frequently used, but theoretically complex, method of noise jamming, and to attach well-defined, quantitative measures to the characteristics of waveforms produced by different FM/N systems. As such, it does three things. First, it gives theoretical consideration to the case of FM/N where the peak frequency deviation of the frequency modulator is smaller than or on the same order as the bandwidth of the modulating noise. This condition is referred to here as narrowband FM/N (NBFM/N). This case is analyzed in order to complement the descriptions of FM/N which consider primarily the effects of wideband FM/N. Second, it details a series of experiments which were performed in order to determine the validity and usefulness of three proposed measures of "noise quality," an indication of the jamming effectiveness of a given signal. It also makes an additional recommendation about the theoretical determination of noise quality. Thirdly, it makes reccommendations for a standardized method of measuring noise quality on operational jammers.

In order to accomplish these objectives, this thesis has been divided into seven chapters. The first chapter is the introduction, intended to give an overview of the entire work.

The second chapter provides a background for the following chapters. First, it gives a brief overview of the importance of noise jamming in the area of Electronic Warfare (EW). Secondly, it explains the the basic concept behind FM jamming, both FM/N and FM by sinusoid plus noise (denoted FM/S+N). Lastly, the second chapter introduces and summarizes two previous efforts which have a direct bearing on the subject of this current thesis.

The first effort was a group of experiments commissioned by the USAF and carried out by a team of scientists and engineers at Stanford Research Institute from the mid 1960's through the 1970's. These experiments measured different characteristics of operational radar jammers and correlated those characteristics with the jammers' abilities to effectively jam. One important result of these experiments was a measure of noise quality which has been used for the last two decades. This measure of noise quality has sometimes been referred to simply as Noise Quality, (20). In other places, it is referred to as Gaussian Noise Quality (GNQ), since it is based on comparisons between a histogram of samples of the noise waveform being measured and the probability density function of an ideal gaussian random process having the same mean and variance (14). Since Turner was the first member of the team to explain this measure of noise quality in the open literature, it has also sometimes been referred to as Turner Noise Quality (TNQ), (8) and throughout this thesis, the term Turner Noise Quality will be most often used. Because many of the noise jammers tested by the Stanford team were FM jammers, their work was foundational to the concepts being studied in this present work, both in terms of the function of an FM jammer and in term of measuring the difference in effectiveness between one type of FM/N jamming scheme and another. Therefore, a brief familiarization with their results is an important prelude to the thesis as a whole.

The second effort was some solid theoretical work on the nature of wideband FM/N, and a small group of experiments which simulated an FM/N jamming system, demonstrated the characteristics of wideband FM/N (WBFM/N), and measured the TNQ of two basic types of WBFM/N systems. This work was reported in *An Analytical and Experimental Investigation of FM-by-Noise Jamming* which was writted by Captain Charles Daly in 1992 (8). The experimental set-up developed by Daly was duplicated in the research reported in this thesis, and many of the recommendations for future experimentation which were made by Daly are carefully considered here. Thus, a brief outline of Daly's work is also an important part of the general background of this thesis.

The third chapter is a literature review. In the context of the background provided in Chapter 2, the third chapter looks at relevant articles and technical reports from the last four decades which touch on FM jamming and the measurement of noise quality in noise jamming. Two recurring concepts are particularly significant in these works: 1) In the works that admit the purpose of their investigation is the analysis of noise jamming, it is generally shown that the optimum noise should have a flat spectrum in the passband of the receiver being jammed, and a gaussian first order probability density function. However, the emphasis in quantitatively measuring noise quality is almost always focused on the gaussianity of the pdf rather than the flatness of the spectrum. 2) In many of the articles, it is shown that the spectrum of the FM jamming signal generally conforms to Woodward's theorem (described in more detail in Chapter 2 and Chapter 4 of this thesis), provided that the peak frequency deviation of the modulator is sufficiently large. This implies that under the best of circumstances, the FM/N spectrum will never be perfectly flat over any bandwidth, and may in fact deviate quite a bit from ideal flatness. These two facts sparked an interest in defining a new standard of noise quality that quantitatively measured whiteness as well as gaussianity. They also lead directly to the discussion in Chapter 4.

The fourth chapter is divided into three general parts: 1) it gives theoretical consideration to the concept of ideal noise, 2) it describes the time and frequency-domain behavior of FM/N both at RF and at the output of the IF filter of a victim receiver, and 3) it gives theoretical consideration to four methods of measuring the conformity of a sampled noise waveform to the characteristics of ideal noise.

The first part merely demonstrates that ideal noise is both white and gaussian. The second part is, in part, a reiteration of the theory explored in (8); however, this thesis focuses on the shape of the RF spectrum of the FM/N signal when the peak frequency deviation of the modulator is too low to meet the requirements for the application of Woodward's Theorem. Throughout the sequel,

this case will be referred to as NBFM/N because of the correspondence to the rough definition of narrowband FM (29).

A full discussion of the spectrum of the wideband FM/N signal is found in (8); however, the NBFM/N spectrum was not described in detail there because it is not intentionally used for noise jamming in practice. The noise produced by NBFM/N is considered to be of a poorer quality than that produced by WBFM/N because of its distinct non-flatness. Nevertheless, there are circumstances (which will be described below) in which Turner Noise Quality (which has been the standard definition of noise quality (30)) actually shows an increase in noise quality with a decrease in peak frequency deviation from WBFM/N towards NBFM/N. An explanation for this observed behavior is developed by considering four possible cases of FM/N jamming based on the relationships between the three bandwidths which must be involved: the bandwidth of the modulating noise, the RF bandwidth of the FM/N signal, and the bandwidth of the victim receiver.

Turner noise quality is described in detail as well as the *IF noise quality* developed in (8). It is noted that Turner noise quality does not depend quantitatively on the whiteness of the jamming signal while IF noise quality does. *RF noise quality*, also developed in (8), is commented on briefly. Additionally, a fourth measure of noise quality is developed and presented.

The most important points to be found in Chapter 4 are the further clarification of the behavior of FM/N from a theoretical standpoint and the provision of further motivation for a standard definition of noise quality which includes a quantitative examination of the flatness of the spectrum.

The fifth chapter describes the experimental setup. Three general groups of experiments were performed. The first group included the experiments which were used to compare and analyze the proposed measures of noise quality. This group of experiments followed directly from the recommendations in (8). Specifically, numerous measurements were made using essentially the same setup described there, but varying some of the experimental parameters and, in some cases,

the computer programs which computed noise quality. One purpose in these experiments was the attempt to find some consistency in a proposed noise quality measure which included a quantitative measure of the flatness of the spectrum.

Also included in this group was a demonstration of the increase in the gaussianity of the noise at the output of the IF filter of the receiver which occurs when the bandwidth of the IF filter is successively narrowed. This phenomenon occurs as a result of the Central Limit Theorem as has been noted by Turner and others (30), (6). The general consensus of scientists and engineers in the field of electronic warfare seems to have been that the bandwidth of the IF filter should be *smaller* than the bandwidth of the modulating noise; yet experimental results from Turner seemed to indicate that once the IF bandwidth was made *as small as* the bandwidth of the modulating noise, there were no benefits (in terms of increased gaussianity) in further decreasing it. Furthermore, a cryptic remark in the work by Daly: (8:3-13)

FM-UBN seems to behave much like FM-WBN.

indicates that this was Daly's experience also. Therefore, it seemed worthwhile to explore this phenomenon thoroughly from an experimental standpoint.

The second group of experiments used a setup similar to that used in the first group, [1] but was designed primarily to demonstrate the central problem with Turner Noise quality as a noise quality measure, which is that Turner Noise Quality does not quantitatively measure the flatness of the spectrum of the noise. Specifically, it shows that under certain circumstances, when the peak frequency deviation of the frequency modulator is decreased, the spectrum of the jamming signal becomes increasingly non-white, yet the Turner Noise Quality actually increases. It is reasonable to expect that a robust measure of noise quality would not do this.

The third group of experiments used a somewhat different setup than that used by the first two groups. It employed the same commercial sampling oscilloscope and modified versions of the

[1] The same simulated jammer and receiver were used, but the computational hardware and software had been changed as a result of lessons learned while performing the first group of experiments.

computer programs and algorithms used in the first two groups of experiments; however, whereas the first two groups of experiments measured the noise quality of a simulated jammer operating in frequencies ordinarily used for communications, this third group of experiments measured the noise quality of an operational radar jammer. The purpose of the third group of experiments was, first of all, to demonstrate that the noise quality of a radar jammer could be measured using commercially available equipment, and, second, to develp a reliable valid technique for making the measurement.

The sixth chapter records the results produced by the experiments described in the fifth chapter. Some of the trivial results are explained verbally, but an effort is made to present characteristic waveforms, spectrums and probability density functions graphically, either by reproducing oscilloscope and spectrum analyzer displays or by showing the results of computer generated sample histograms. General trends are also supported with graphs.

The seventh chapter presents conclusions and recommendations for further work. Some conclusions about the natures of the different types of FM/N systems were obviously supported by both theory and experiment. Others are offered as tentative observations which may be verified or explained more adequately by future researchers. Several questions were raised in the course of the research and experimentation reported in this thesis which could not be adequately answered under the time constraints which were imposed, and it is hoped that future researchers may consider them.

The appendices at the end are provided to facilitate further research in this area. The first appendix includes listings of the computer programs written in C and Matlab to measure noise quality on both the FM/N system simulation and the operational jammer which operated at frequencies typically used by radar. Listings of the programs which were used to make measurements on the simulated jammer can be found in Appendix A of (8). Such modifications of those programs as are suggested as a result of lessons learned from the experiments reported here are found in Chapter 6 of this thesis.

The second appendix lists the raw data which was collected from all three groups of experiments in both tabular form. Some comments, conclusions and graphical analysis of this data are found in Chapter 6 of this thesis.

II. Background

The purpose of this chapter is to introduce and explain the proposed research into the optimization of noise quality measurements in radar noise jamming. There are two aspects to this research. The first involves a mathematical analysis of currently used and proposed noise quality measures. The second involves experimental measurements of noise quality using the different noise quality measures.

Before describing the specifics of either the mathematical analysis or the experimentation, a short introduction is provided on radar jamming and noise quality measurements. Particular attention is paid to Turner noise quality, a measure of noise quality which was developed in the late 1960's to classify the noise quality of operational jammers in the United States Air Force inventory (30).

Following the introduction, there is a discussion of the current methods of measuring noise quality. Recent research has provided two new proposed measures of noise quality which need to be explored analytically and experimentally. The specifics of these two new measures, how they are defined and how they can be measured in a laboratory, will be given some attention. These measures will also be compared briefly to Turner noise quality, and an explanation of how they are sufficiently different from Turner noise quality to warrant investigation will be offered.

2.1 Introduction to Noise Jamming

The subject of noise quality in radar noise jamming techniques might best be introduced by defining noise jamming in radar systems. All radar systems consist of a radio transmitter (or transmitters) and a receiver (or receivers). Specific receivers vary widely in design depending on the intended application of the radar system, but all radio receivers, in radar systems or otherwise, are designed to detect meaningful electromagnetic radiation (signal) in the presence of meaningless radiation (noise). A graph depicting probability of detection and probability of false alarm in a

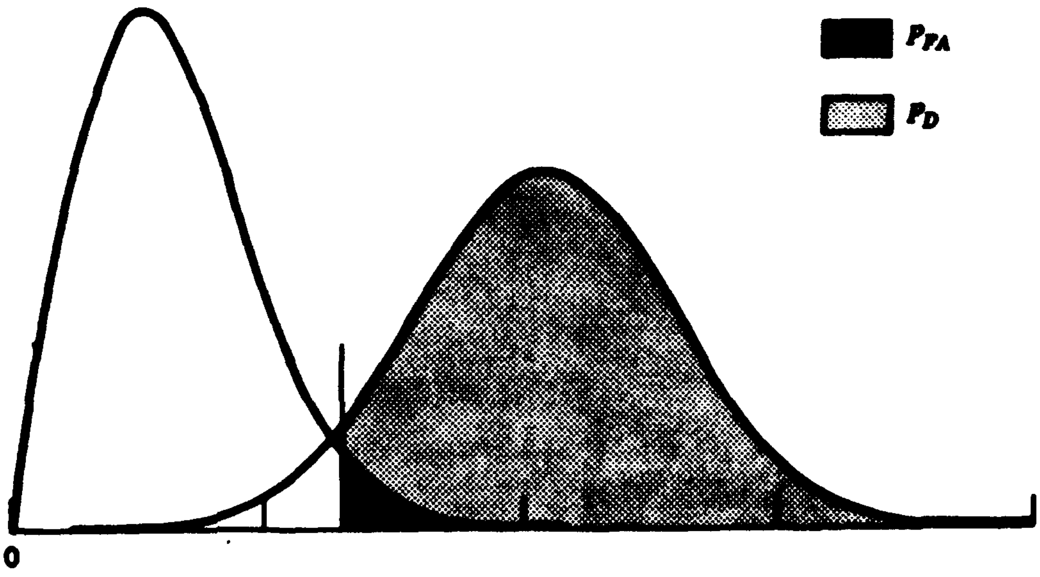


Figure 1. Probabilities of Detection and False Alarm

radar system in the presence of gaussian noise is shown in figure 1 above, to illustrate the basic problem. As the amount of noise energy becomes large with respect to the signal energy, the peak of the noise energy probability distribution moves closer and closer to the peak of the distribution of the signal plus noise until they become virtually indistinguishable, in a statistical sense.

Ordinarily, the greatest source of the meaningless radiation is the radar receiver itself. Resistive elements inside the radar receiver produce random electrical currents because of thermal vibrations of the component electrons when the radar system is at any temperature above absolute zero (29). The first order probability density of these electrical currents is gaussian, and they generate a power spectrum with constant power in all frequencies from DC up to about 10^{12} Hz. This nearly constant power spectrum is flat enough over enough frequencies that for all practical purposes we will refer to it as "white." To the radar system, these random electrical currents generated by the radar receiver itself are indistinguishable from the currents generated by the incident electromagnetic radiation which the radar system is designed to receive.

A certain level of noise power can be tolerated, so long as the signal power is sufficiently large by comparison, but, for each receiver, there exists a lower limit in the ratio of signal power to noise

power beyond which the output of the receiver cannot be characterized as having any correlation to the desired signal. This limit is known as the signal to noise ratio threshold, and although it can be lowered somewhat, at the expense of more sophisticated signal processing techniques, or longer observations of a relatively consistent signal, it cannot be made arbitrarily small. Radar noise jamming, then, is an electronic countermeasure that seeks to deny meaningful information to the operator of an opposing radar system by delivering sufficient noise power to the radar system's receiver to drive the receiver below its signal to noise ratio threshold. This is a simple concept, but because noise is such a fundamental physical limiter in the operation of receivers, radar noise jamming is still the most common electronic countermeasure used (22).

Often noise jamming is referred to as "masking jamming" because the purpose of the jamming is to obscure or "mask" any signals which the victim radar receiver is interested in intercepting. Masking jamming is fundamentally different from deception jamming which is used to confuse the victim radar receiver operator. Deception jamming is more sophisticated than noise jamming, but for that very reason is not always as reliable.

The concept behind noise jamming may be simple, but the application is more complex. First of all, not all noise is equivalently useful in noise jamming. In order to be effective against a particular radar system, the noise must be received by the targeted system. This requires that the noise contain frequency components that lie within the bandwidth of the receiver. Secondly, in order to be conservative of power, it is desirable that a radar jammer employ noise that is frequency limited to the bandwidth of the targeted receiver. Thirdly, the noise must be generated within the constraints of relatively deterministic circuitry, yet it must not be deterministic (if it were predictable it could be eliminated at the targeted receiver by signal processing).

This third problem has an immediately suggested solution in that all resistive elements in a circuit produce noise with characteristics as mentioned above. If noise is commonly generated inside the targeted radar system by resistive circuit elements, then it may be generated by similar

elements outside, and then broadcast as electromagnetic radiation directly into the radar receiver. In actual practice, the noise power of resistive noise is so small, even when greatly amplified, that it is difficult to use it as a noise source, and other circuit elements such as back-biased diodes (13) are often employed to produce low-level noise with the appropriate characteristics; however, this brings us to the fourth problem: the noise must be broadcast at radio frequency with a sufficient power level to drive the targeted receiver below threshold, but both the broadcasting and the power amplification have some deterministic effects on parameters that characterize the noise. These deterministic effects may or may not change the noise sufficiently so that it becomes predictable enough to be canceled at the receiver through signal processing.

More than a few techniques for generating radio frequency noise targeted to specific radar receiver bands, amplified to high levels and sufficiently non-deterministic to defeat any signal processing counter-counter measures have been designed and used since the advent of radar, although almost all of them function along the lines of the general principles outlined above: simple low-level noise is produced by a circuit, it is filtered to some frequency band, it is amplified to sufficient power levels, and then it is directly broadcast (if it is already at the appropriate radio frequency) or used to modulate (either AM or FM) an RF carrier. Occasionally, the noise is amplitude clipped before broadcasting. Sometimes a sinusoid is added to the noise to increase the noise bandwidth. A recent innovation in electronic countermeasures is the Digital Radio Frequency Memory (DRFM) which is most often used for deception, but which can be used to broadcast noise at RF, if the memory is loaded with the appropriate radio frequency noise.

When noise is generated in the appropriate frequency band and merely amplified and broadcast, this technique is known as Direct Noise Amplification or DINA. When the noise is used to modulate a carrier at RF, then the technique is referred to as either AM-by-noise (AM/N) or FM/N, as appropriate. In the early decades of radar noise jamming, all three techniques were implemented in operational radar jammers; however, DINA and AM/N were found to have some

drawbacks in terms of efficient use of the microwave amplifiers or efficient use of the bandwidth, so that in 1983, Golden writes (11:192):

> There are basically two ways of constructing a noise jammer: direct noise amplification (DINA) and frequency modulation by sine wave plus noise (FM/S+N).

And he goes on to explain why the FM jammer makes more efficient use of the microwave amplifier. But at this point, rather than discussing how to produce noise under the constraints listed above, the discussion will turn to what constitutes "good" noise under those constraints.

2.2 Noise Quality in Jamming

The foundation for the theory of noise quality is found in information theory developed by Shannon (24). A fuller development, based on the concept of information entropy, is presented in Chapter 4. The essential result is that the worst possible noise, in terms of destroying information in a communications channel, is noise which has a flat power spectral density and a gaussian probability distribution function (25). This noise is commonly referred to as "white gaussian noise." This result has an intuitive appeal. As was pointed out above, the noise which every radar system must endure in the course of its normal operation is, to a large extent, resistive noise, which is gaussian and essentially white up to very high frequencies. Thus, the noise which should be injected into a communication channel in order to most degrade the information passing through that channel is noise which is indistinguishable from the noise generated internally by the receiver itself.

The next question to be answered then, in terms of noise quality, is, how should power spectral densities and probability distribution functions of a non-deterministic wave-form be measured? This question was and is important, not only for the purpose of analytically verifying a noise-jammer design, but also for the purpose of testing the finished product. Before sending an operational jammer to perform a specific mission, it is useful to know whether the jammer actually produces noise that will jam effectively.

Engineering a setup to measure the probability distribution functions of noise produced by noise jammers was the subject of a study commissioned by the United States Air Force in the late 1960's (20). A team at Stanford approached the problem by jamming a receiver with the noise jammer under investigation and then making measurements on the time series of the output of the victim receiver's intermediate frequency filter.

Now it is important to note that noise was not measured at radio frequency. There were two reasons for this. The first was that most receivers at that time did not bandlimit their inputs until after heterodyning to an intermediate frequency, and the relative spectral whiteness of the noise is only relevant in relationship to the frequency band that is being jammed (i.e. the bandwidth of the victim receiver.) The second reason is that while DINA produces an RF signal that is bandlimited white gaussian noise, as would a DRFM which was loaded with digital noise and used for noise jamming, the AM/N and FM/N signals at RF are neither gaussian nor white. Whether or not an AM/N or FM/N signal will produce bandlimited white gaussian noise in the output of the victim receiver is highly dependent on the precise characteristics of the noise jamming system in relation to the characteristics of the victim receiver. Thus in comparing one noise source with another it was important to normalize out the factors which were related to how the jamming was done, and focus instead on the ultimate effect of the jamming in a given receiver.

The first order probability density of the victim receiver output time series was computed, and that was compared to the probability density of an ideal gaussian random variable scaled to have the same mean and variance as the measured time series. Several error measures were then computed. Average error, rms error, and summed error; kurtosis and skewness; and the relative entropy of the measured output were originally used as the basis of three individual measures. Later they were combined by Turner and others to form the measure known as Turner noise quality in 1977(30).

Turner Noise Quality is defined as:

$$\frac{1}{\text{Noise Quality}} = \frac{1}{3}\left(\frac{e_s + e_a + e_r}{3} + |\text{relative entropy in bits}| + \frac{|k-3| + |s|}{2}\right) \quad (1)$$

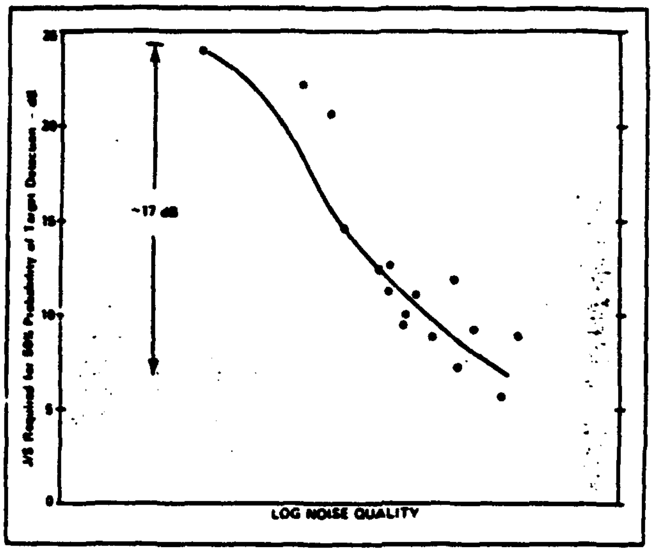
where e_s is the summed error, e_a is the average error, e_r is the rms error, k is the kurtosis, and s is the skewness,

$$0 \leq \text{noise quality} \leq \infty. \quad (2)$$

In actual practice, a very good gaussian noise source will have a large noise quality (some have been measured as high as 70) while a non-gaussian source should have a relatively low noise quality (for example: a perfect sinusoid has a theoretical noise quality of 1.5).

The practical value of the Turner Noise Quality measure was demonstrated by a series of experiments carried out by Turner, Ottoboni and Imada at Stanford, and reported on in 1977 (30). A white gaussian noise source was amplified and then lowpass filtered. The output of the filter was then used as the input to a solid state voltage controlled oscillator and FM modulator. The RF signal at the output of the FM modulator then had characteristics which were similar to those of signals produced by many of the most common operational jammers, and these characteristics could be modified (by being more or less white in a particular bandwidth) by varying the bandwidth of the lowpass filter, the amplitude of the white gaussian noise source, or the parameters of the FM modulator. Furthermore, when the RF signal was broadcast into an operational radar system that was hooked up to it, it was mixed down to an IF frequency and passed through a bandpass filter. By altering the bandwidth of the baseband noise with respect to the bandwidth of the IF filter of the victim receiver it was noted that the output of the IF filter could be made more or less gaussian. The unit as a whole was referred to as a Gaussianity Test Source.

The output of the Gaussianity Test Source was monitored by a computer controlled probability density analyzer which sampled the output signal and then computed the various parameters of the Turner noise quality measure in order to report the Turner noise quality in near real time.



1. J/S vs. noise quality for linear receiver/A scope display. White Gaussian noise provides the highest quality, allowing a 17 dB reduction in jamming power.

Figure 2. J/S versus Noise Quality with fixed P_d

Once the noise quality of the signal was determined, it was used to jam conventional pulse radar systems in the presence of signals generated by a sophisticated radar simulator. Experienced radar operators then monitored the display scopes of the radar receivers and attempted to accurately determine the presence or absence of a real target in the midst of the noise. A long series of experiments in which several thousand operator detection decisions were made demonstrated that there was a rough inverse relationship between the jamming power required to obscure a target (as measured by J/S, which is the ratio of jamming power to target signal power) and the Turner noise quality. As the Turner noise quality increased, a smaller J/S was required to significantly decrease the operators' probability of target detection. As shown in Figure 2 taken from (30), a very good noise source required roughly five times less power than a very poor noise source to effectively jam a conventional receiver.

The correlation between noise quality, as measured by Turner, and jammer effectiveness, as demonstrated by the experiment outlined above, is a strong argument in favor of the validity of the Turner noise quality measure.

It is interesting to note that all these measures were based on the probability distribution; none of them dealt with the uniformity of the power spectral density. That the members of the team were aware that the optimal noise should be white as well as gaussian is well documented (20). However, because of the limitations of the measuring equipment available at that time, their approach to measuring the whiteness of the noise was entirely qualitative rather than quantitative. The shape of the spectrum was observed, using a frequency analyzer, and then a decision was made, based on its conformity, or lack thereof, to the theoretical shape of the IF filter, as to whether the noise seemed to be sufficiently flat in the passband of the IF filter to be called white. If it was, then the noise was considered acceptable and the Turner noise quality was computed. If the noise did not seem to be sufficiently flat, then it was rejected, and its gaussianity or lack thereof was not considered. Documentation of this procedure was included in the technical report in the form of Polaroid pictures of the frequency analyzer displays pasted in next to the results produced by the probability density analyzer.

As the members of the team pointed out, almost all of the jammers which they tested had power spectrums which were nearly flat over almost every frequency that was tested. (20)

2.3 Current Techniques in Measuring Noise Quality

Turner noise quality was consistently used as the primary theoretical measure of the effectiveness of operational jammers up through the 1980's. As evidence of the universal acceptance of the ad hoc measure, we note that in 1985, a simulation program based on the Turner noise quality measure was proposed as a method for optimizing noise jammer design. (14) The test setup designed by the team as Stanford has long since been disassembled; however, with new jamming techniques there has been a renewed interest in measuring noise quality and in 1991 a study of FM/N jamming was sponsored by Wright Laboratory (WL/AAWA) and carried out by Captain

Charles Daly. Because this present thesis is partly a continuation of the effort begun there it will be appropriate to give a brief summary of that recent work.

The focus of *An Experimental and Analytical Investigation of FM-By-Noise Jamming* (8) was a thorough explanation and demonstration of FM/N. It accomplished this by reviewing the literature on FM/N, deriving or citing the equations which describe the behavior of FM/N, and, lastly, constructing a laboratory simulation of an FM/N jammer and a victim receiver and measuring the noise output of the receiver. The last part of the thesis would have successfully demonstrated the operation of FM/N if it had merely produced reproductions of the oscilloscope and spectrum analyzer traces showing the time and frequency domain characteristics of FM/N signals. Daly's work did this; however, it also produced a new setup for duplicating the Turner noise quality measurements.

There were some differences between the Daly setup and that used at Stanford. For example, the Stanford setup builds a histogram of voltage levels based on five million samples, while the Daly setup uses only a few thousand samples. The Stanford setup sorts voltages into either 512 or 1024 bins while the Daly setup usually uses around 30 voltage bins. The Stanford setup was designed to measure the noise quality of radar jammers at frequencies ordinarily used by radar, and actually measured operational radar while the Daly setup operated at frequencies of less than 1 GHz, and was primarily intended as pure simulation to demonstrate a concept. However, it should be noted that the Stanford setup was the result of specially engineered equipment, while the Daly setup exclusively used equipment which is commercially available.

Two important things came out of the Daly investigation into FM/N which have a direct bearing on this thesis. The first is a proof of Woodward's theorem which is given in Chapter 4 (8). The second is a practical recommendation that two other measures of noise quality should also be investigated.

2.3.1 Woodward's Theorem. Woodward's theorem has been mentioned previously in this thesis but has not yet been defined. Because it is an important theorem in describing the spectra of a WBFM signal in general, and particularly important to the description of the WBFM/N spectra, an informal description of it will be included here. In an FM system, the frequency output of the system is directly related to the voltage level of the input. Thus if an input is a constant offset voltage, one would expect the RF spectrum of the FM system to be dominated by a single frequency component at a constant offset from the nominal carrier frequency. And, for a general modulating signal, we would expect the RF spectrum to have large frequency components corresponding to voltage levels that the modulating signal visited frequently, and small frequency components corresponding to voltage levels that were rarely visited. Or, to state it another way, it is anticipated that the shape of the RF spectrum will generally correspond to the shape of the univariate probability density function of the voltage level of the baseband noise (28:307).

2.3.2 IF and RF noise quality. Of the two new noise quality measures proposed by Daly, the first of these measures is called *IF noise quality*, and, like Turner noise quality, it measures the gaussianity of the output of the targeted receiver directly after the IF filter. Unlike Turner noise quality, it also makes a quantitative measure of the whiteness of the spectral density of the noise and imposes a penalty for a power spectral density in the passband of the IF filter which deviates from absolute flatness. It seems intuitively appealing that the IF noise quality would be able to distinguish more clearly between a good noise source and a poor noise source than the Turner noise quality because it contains information about the frequency domain characteristics of the noise as well as the time domain characteristics. However, as was observed by Turner and the research team at Stanford, under most conditions, the spectral densities of most noise jammers are reasonably white, leading to the result that IF noise quality and Turner noise quality are most often relatively equivalent.

IF noise quality calculates a "time-domain penalty" (p_t) by essentially calculating the error in the difference between a histogram of the voltage samples in the IF noise and a theoretical gaussian histogram - a technique very similar to that used in a portion of the Turner noise quality measure. The value p_t has a maximum value of one. IF noise quality also calculates a "frequency domain penalty" (p_f) by taking the ratio of the measured jamming power to the ideal power over the range of the 3dB bandwidth of the IF filter of the receiver. Thus, (p_f) should be between zero and one. The two penalties are then combined to form the IF noise quality ρ_{IF} by the formula:

$$\rho_{IF} = (1 - p_t)(p_f) \tag{3}$$

Perfectly white and gaussian noise then would have a ρ_{IF} of 1 (or 100%) while any noise that deviated from perfection would have an IF noise quality that was some fraction of that, or, in some extremely poor cases, a negative value (8).

RF noise quality is the second of the new proposed noise quality measures, and it differs dramatically from Turner noise quality. It is a measurement made at radio frequency (RF) rather than at IF and it is based on frequency domain measures alone rather than on time domain measurements (as does Turner noise quality) or time and frequency domain measurements (as does IF noise quality). It represents a rather clever analysis from a mathematical perspective, but its results are only valid under the specific type of noise jamming (FM-by-noise jamming) which was the primary focus of the investigation sponsored by Wright Laboratory.

In FM/N jamming, a low-frequency noise source is used to frequency modulate a carrier centered on the receive band of the targeted receiver. Under these circumstances, Woodward's Theorem states that the power spectral density of the RF signal will have the same shape as the probability density function of the modulating signal. Therefore, a chi-square goodness-of-fit test can be applied to the power spectral density of the RF signal to determine whether the low-frequency noise was truly gaussian, and so, whether the noise at the output of the IF filter of the

target receiver is gaussian. Since measuring the power spectral density of a waveform is much easier than computing the first order probability densities, this is a great advantage.

However, the problem with this portion of the RF noise quality measure, as a general noise quality measure, is that the shape of the power spectral density of an RF noise waveform that was not generated using FM/N should not necessarily have a gaussian characteristic (for example, DINA noise or noise produced from a DRFM may be of a high quality, but would not receive a good RF noise quality figure).

Furthermore, the efficacy of an arbitrary signal in producing gaussian noise in a victim receiver cannot necessarily be established simply by looking at the RF signal. DINA noise has a gaussian pdf at RF and produces gaussian noise in a victim receiver at IF. But, as noted above, although the RF signal generated by FM/N jammer has a gaussian spectrum, it is *not* a gaussian process and does not have a gaussian probability density function. Rather, it is more properly characterised as a sinusoid of varying frequency, and it tends to have a voltage histogram (a rough measure of the true probability density function) that is characterized by a local minima at the mean voltage and two local maxima (one being the absolute max), one above and one below the mean voltage, in sharp contrast to the voltage histogram of a gaussian noise signal which has an absolute maximum at the mean voltage. It is only when the RF signal is heterodyned to an IF frequency and passed through a filter of sufficiently narrow bandwidth that the output of the filter resembles gaussian noise.

Furthermore, RF noise quality is unique among noise quality measures in that the measurements taken are independent of any parameters of the victim receiver which is being jammed. Because the efficacy of any noise jamming system is heavily dependent on what victim system it is trying to jam, this again makes the measure problematic as a general measure of noise quality. This dependence of the efficacy of a noise jamming system on the parameters of the victim receiver

being jammed is one of the reasons why the team at Stanford avoided using any such measure, as noted above.

Thus RF noise quality is a potentially useful measure of noise quality in FM/N jamming when noise quality is not normalized to the parameters of a specific victim receiver being targetted, but it cannot be blindly applied to an arbitrary noise source.

RF noise quality is based on measurements made at RF, and it uses those values to compute time and frequency domain penalties and then combines them via the same equation used for IF noise quality.

2.4 Summary

In concluding this chapter, it is important to note the following points: First, that noise jamming, because of the fundamental physically limiting nature of noise in radar receivers, is an important technique in electronic warfare. Second, that "ideal noise" for noise jamming is noise which is both white (in the frequency range being jammed) and gaussian. Third, that the noise employed in noise jamming must be generated in some non-deterministic fashion and broadcast in a specific frequency range and thus is unlikely to have the ideal characteristics of purely resistive noise merely by accident or coincidence. Thus, some jammers will have characteristics that are more ideal than the characteristics of others, based on their design.

Fourth, recall that jammers which produce more ideal noise (primarily in terms of more gaussian first order probability densities) have been experimentally shown to mask targets better at lower J/S ratios. And, last, that there are currently three quantitative measures of noise quality. One of these measures (Turner noise quality) has been rigorously experimentally verified and was universally used for the last 20 years or so; however, it only gives a quantitative measure of the gaussianity of the noise, and addresses the question of whiteness only qualitatively. The other two

measures of noise quality were proposed in the last two years, and they attempt to employ the better equipment available today to improve on Turner's work.

III. *Review of the Literature on Noise Quality and FM/N and FM/S+N*

The purpose of this chapter is to review the EW literature which relates to FM noise jamming and to the measurement of noise quality in noise jamming. Much of the early material in the field of EW in general is either indirect or classified because of security considerations. However, the basic theory of FM noise jamming was developed and experimented with sufficiently long ago that most of the relevant classified documents are now unclassified, and the more indirect articles have been clarified by more direct later material. This leaves us with several distinct categories of material to look at. Firstly, there are articles in the open literature from the 50's and into the 60's which speak indirectly about the spectra of signals which are frequency modulated by low frequency noise. Secondly, there are technical reports on experiments and theoretical work done with FM/N and FM/S+N jamming which were classified at one time but which have since undergone declassification. Thirdly there are more recent articles, EW texts and theses which deal with the theory behind FM jamming in a forthright manner.

For a very good review of the literature on FM/N from the perspective of a theoretical and experimental description of FM/N at both RF and IF, one should consult Chapter 2 of the work by Daly (8). Although only one declassified technical report is alluded to there, the research of articles and EW texts is very thorough and it covers the essential topics of what categories of jamming FM/N can be placed in, what kind of spectra it generates at RF, and how it is used to jam the IF filter of a receiver, and even touches briefly on the material surrounding the rather obscure topic of FM-by-erfer noise. (Ordinarily when FM/N is spoken of in EW literature, the noise at the input of the FM modulator is assumed to be white gaussian noise, bandlimited to some baseband frequency.)

The emphasis in this present thesis, however, is not so much on the theory of the function of FM/N (with the exception of NBFM/N) but rather on the characteristics of the noise produced by FM noise jamming and the concern of the authors of the various materials to produce noise that had

certain characteristics. Additionally, there is emphasis on the techniques that were suggested and implemented to determine the degree of presence or absence of these characteristics. Accordingly, this chapter deals with three different types of material. The first type is material that describes the optimal characteristics of a noise jamming signal. The second is material that describes the characteristics at IF and RF of signals arising from FM/N and FM/S+N, and the third is material that deals with the subject of noise quality measurement.

Because some articles and almost all of the technical reports and texts deal with more than one of these subjects, if each subject were considered separately, there would be multiple citations of many of the sources. (For example, Golden spends some time discussing optimal noise (p 92), then later turns his attentions to types of active jamming systems (p 199) (11).) In order to avoid this kind of redundancy, this chapter is composed of sections that first consider early open literature articles and papers that refer to FM jamming indirectly, then look at declassified technical reports, and more recent articles, texts and theses that deal openly with FM/N and FM/S+N as EW techniques. However, in each of these sections, the material will be looked at as it relates to each of the subjects mentioned above, and it is hoped that certain recurring themes will be noticed. A section summarizing the important points is found at the end of this chapter.

3.1 Early Articles in the Open Literature

The earliest papers that address the concept of FM/N are almost all concerned with the shape of the spectrum produced by FM/N or phase modulation by noise (ϕM/N), and have little or nothing to say about the statistical characteristics of the FM/N signal. The most probable reason for this is that from the perspective of the radar jammer designer, the probability density function of the RF jamming signal is not really all that important; he is more concerned about the probability density function of the *detected* signal that comes out of the victim radar's IF filter. For security reasons, the writers of the early articles avoid direct mention of noise jamming, but

the fact that much of their research was sponsored by military organizations makes it more than likely that they were working on the radar jamming problem and, therefore, if they were interested in the statistics of the FM/N signal, they would only have been interested in the statistics from the perspective of a radar jammer designer. Thus, in terms of probability density functions, the problem they were interested in was precisely the problem that they were prohibited from discussing in the open literature.

In 1951, David Middleton presents a paper on the spectra of carriers amplitude, phase and frequency modulated by gaussian noise (17). His presentation begins by assuming ergodicity, finding the autocorrelation function of the RF signal, and applying the Weiner-Khintchine theorem. His approach is a little unusual in that he assumes a modulating noise with a gaussian spectral density as well as gaussian amplitude characteristics, while most noise models assume the power spectrum of the noise to be either white or rectangular between two frequencies. While the final expression which he obtains is the result of a rather unwieldy MacLaurin series expansion that does not, by itself, readily give much insight into the shape of the FM/N spectrum, he offers some observations in addition, such as explaining under what conditions there will be a discrete amount of power in the carrier frequency or in certain harmonic frequencies, and when (as is more common) the carrier power is distributed throughout the continuum. He also is the first to distinguish between modulating gaussian noise which has spectral components at zero frequency and that which has spectral components which are merely close to zero frequency. His most important statement from the perspective of this thesis is (17:699):

> Note that as the mean intensity of the modulating noise (ω_b) becomes very small, or as the r.m.s. deviation (ω_d or θ_d) becomes very great, the other parameters of the system remaining constant, *one always approaches a gaussian modulation spectrum, quite independent of the precise power distribution of the modulating wave* ...

Although the point of the quote may seem a little obscure without a thorough understanding of the symbols Middleton is using, or the precise context, it is essentially a specific application of Woodward's Theorem. In essence, Middleton is saying that when the peak frequency deviation

of the modulator is sufficiently greater than the highest frequency components of the modulating noise, it doesn't really matter what the precise shape of the spectrum of the modulating noise is: all that matters is the univariate probability density of the noise, which in this case happens to be gaussian. Under those circumstances, the shape of the RF spectrum will approach gaussianity.

The technical report produced by Stewart in 1953 is more lengthy and more narrowly focused, but it begins with a similar statement (26):

> It should not be inferred that a knowledge of the power spectrum of a frequency- or phase-modulated carrier tells a great deal. In fact, the power spectrum of FM or ϕM yields much less (relative) data than that of an amplitude-modulated wave. For example, if the frequency deviation of an FM signal is larger than the bandwidth of the modulating voltage, the shape of the spectrum is essentially independent of the spectrum of the modulating signal.

Stewart's presentation differs from Middleton's in several respects. Firstly, it deals with gaussian noise with a rectangular power spectrum rather than the gaussian spectrum dealt with by Middleton. Secondly, it produces a set of asymptotic closed-form expressions for the shape of the RF spectra (i.e. the spectra conforms to these expressions asymptotically as certain parameters are made arbitrarily large) which are presented graphically, and thirdly, it deals exclusively with phase and frequency modulation and does not touch on the subject of AM/N (which has been shown to be less effective as a jamming technique).

Because of the simplicity and clarity of the closed-form expressions derived by Stewart, they are shown below:

$$W_F(\Delta\omega) = \frac{A^2/2}{\sqrt{2\pi}D_o} e^{\frac{-\Delta\omega^2}{2D_o^2}}, D_o/B \gg 1 \tag{4}$$

$$W_F(\Delta\omega) = \frac{A^2/2}{\pi B} \frac{\pi D_o^2/2B^2}{(\pi D_o^2/2B^2)^2 + (\Delta\omega/B)^2}, D_o/B \ll 1 \tag{5}$$

where:

A = peak amplitude of carrier voltage,

D_o^2 = mean-squared instantaneous radian frequency deviation (proportional to the mean-squared modulating voltage),

$\Delta\omega$ = radian difference frequency from the unmodulated carrier frequency,

B = radian bandwidth of the modulating voltage

and the power spectrum of the modulating signal is uniform from zero to B radians, and zero above that point (26). The frequencies have been shown in radians rather than Hz so that the first equation becomes easily recognizable as a gaussian shape with variance D_o^2, which perfectly exemplifies the expectations of Woodward's theorem. The second equation, of course, is distinctly non-gaussian. Note that the first condition is what we would call WBFM/N and the second condition is the extreme case of NBFM/N where the peak frequency deviation of the RF signal is actually less than the bandwidth of the modulating signal.

After deriving the closed-form asymptotic expressions, Stewart also spends some time dealing with the corrections which should be applied when one is not at either the WBFM or the NBFM extremes. Specifically, he states that there are two distinct cases when the baseband noise bandwidth is on the same order as the rms frequency deviation of the modulator: 1) when the modulating noise spectrum extends all the way to DC and 2) when the modulating noise extends down only to some lower cutoff frequency. In the first instance he produces a correction expression for the tails of the RF spectrum. When he gives some attention to the question of how the spectrum is changed when the modulating noise has a spectrum which is rectangular but does not extend all the way to DC, he finds that the major difference is that the FM/N spectrum gains a delta function at the carrier frequency; however, he concludes that the effect of the delta function is slight as long as the lower cutoff frequency is small in comparison to the bandwidth of the modulating signal.

Between 1953 and 1957, there is a continuing discussion in the literature about the exact nature of the FM/N spectrum (the ϕM/N spectrum having become less of a concern) where questions were raised and responded to concerning the applicability of Stewart's expressions for the case where the modulation index is moderate or low (the modulation index being the ratio of the modulating bandwidth to the rms modulated bandwidth) (16) (27) (12).

In 1957, Middleton and Mullen respond to Stewart's work and to this entire discussion in a letter in the proceedings of the IRE (18). They agree that Woodward's theorem generally holds when the modulation index is high, and also that there are two separate cases when the modulation index is low. However, they go into much more detail explaining a "suitable expression" for the tails of the RF spectrum through the derivation of an approximating series. In this letter, they use a band-limited white spectrum for the modulating noise rather than the gaussian spectrum which Middleton worked with previously. Additionally, they use an analytical technique which assumes a complex modulating wave and discovers the real RF spectrum through Hilbert transforms. The equations are too lengthy to be included here but they indicate a spectrum that is more peaked, roughly more triangular than gaussian in shape. It should be noted that they seem to have satisfied the other participants in the discussion.

While the issue of the RF spectrum of the FM/N signal was fairly settled at this point, there were a number of other issues which had some indirect bearing on the topic which continued to be raised. Blachman presents a short article on Fourier Series representations for gaussian noise which discusses the independence (or lack thereof) of the Fourier Series coefficients, depending on the fundamental period of the series (3). Later Blachman writes another article which deals only peripherally with FM/N, but deals primarily with the spectrum of FM/S+N. (4) He begins by discussing Woodward's theorem and the places where Woodward's theorem does not hold. First of all, he notes, Woodward's theorem does not hold when the modulation index is low, although it may be a first step towards an approximation. Secondly, Woodward's theorem does not hold when

the baseband modulation is deterministic in such a fashion that it leads to spectral lines in the RF spectrum (modulation by a sinusoid being a prime example). Why is this? The answer can be explained in terms of the "resolution" of Woodward's theorem.

Blachman refers to a non-rigorous but intuitive proof of Woodward's theorem which was understood within the community prior to Woodward's paper on the subject. If we think of a filter-bank in the RF spectrum being connected to the output of an FM modulator, we can imagine the baseband signal sweeping into a particular voltage region and causing the RF signal to sweep into a particular frequency range and then measuring the power that is passed by the filter that covers that frequency range, and thus, by measuring the power passed by each filter, over time, develop a power spectral density for the RF signal. The question is, how narrow should each filter be made in order to have accurate results from this technique? Blachman's response:

> ...the duration of the transient response of the filter must be small compared to the ratio of the filter bandwidth to the rate of change of frequency. Since the duration of the transient response is of the order of magnitude of the reciprocal of the filter bandwidth, this means that the filter bandwidth must be large compared to the geometric mean of modulation bandwith and frequency excursion ...Thus Woodward's theorem can resolve only those spectral details whose widths are much greater than the geometric mean of the modulation bandwidth and the frequency excursion.

(3)

Fortunately for us, it is possible to increase the resolution of Woodward's theorem by including more terms of an infinite series of which the probability density function of the modulating signal is only the first term. This is essentially what was done by Mullen and Middleton in 1957. Also it is possible to generalize Woodward's theorem to cover deterministic modulating signals as well as random signals, and combinations of random and deterministic signals. This leads into the main thrust of Blachman's article, which is the consideration of the spectrum of FM/S+N. Blachman does not say so, but classified reports of about this time were studying the effects of FM/S+N jamming, and finding that adding a sinusoid to narrowband gaussian noise was one way to increase the bandwith of a jamming signal without losing significant gaussianity in the signal at the output

of the IF filter of the victim receiver. Blachman's development shows this increase in bandwidth, but, consistent with other articles in the open literature of this time period, does not touch at all the issue of the statistical characteristics of the output of an IF filter receiving the FM/S+N signal.

Norman Abrahamson offers a paper in 1963 on the bandwidth and spectra of FM and ϕM waves which considers sinusoidal carriers and gaussian random processes as modulating signals. Its purpose is not accuracy in developing an expression for the FM/N spectrum, but rather simplicity and generality. He also has some very informative graphs which show how altering parameters of the modulating noise can change the RF spectrum. The approach is really nothing more than a clarification or perhaps a clever implementation of the approach used by Middleton more than a decade earlier, but because of the simplicity and generality of the Abrahamson's implementation, the equations he presents will be expanded on in considerable detail in Chapter 4, when the theory of the shape of NBFM/N signal is derived.

The last paper in this category is by Blachman, 1969 (5). It again deals with Woodward's theorem and Blachman's filter-bank proof. This proof is finally made rigorous, and, as a result, an upper bound on the error of the approximation indicated by Woodward's theorem is found. He uses gaussian noise with a butterworth (rather than rectangular or bandlimited white) spectrum as his modulating noise, and he generates a series of graphs showing the difference between the calculated RF spectrum and the Woodward approximation for various modulation indices. As the modulation index is high, the Woodward approximation is very good, as it is lower, the actual calculated spectrum is not gaussian at all, but looks very much like a spike at the carrier frequency, as predicted by all the previous work. The fundamental contribution of this work is the new upper bound on the error associated with the Woodward approximation.

3.2 Declassified Documents

Probably the most important declassified document on electronic warfare in general is the massive compilation *Electronic Countermeasures* (6). In Chapter 12, Morita and Rollin discuss types of "masking" jammers (as opposed to deception jammers. Spectra are shown for FM/N and FM/S+N as well as for the other jamming techniques (DINA, AM/N where the noise is clipped, AM/N + FM/S), and, although specific equations are not given, it is apparent that the FM/N RF signal has a gaussian spectrum and the FM/S+N has the desirable characteristic of a broader bandwidth. Comments are made about the relative effectiveness of different jamming techniques, but these comments are fairly general. The whiteness or lack thereof of any of the spectra is not dealt with except to say that noise power should be distributed over the bandwidth being jammed rather than concentrated in a discrete carrier. However, the following quote concerning clipping of DINA:

> If the receiver bandwidth is narrow compared to the clipped noise bandwidth, the noise signal will appear to be gaussian to the receiver and will have the same effectiveness as gaussian noise.

(6:12–5) shows that there was a concern about the gaussianity of the time-statistical characteristics of the noise coming out of the IF filter of the receiver.

Also, in chapter 14 of *Electronic Countermeasures* Benninghof, Farris, Lauderdale and others discuss the effectiveness of different jamming signals. Their discussion begins by calling attention to the fact that different types of jamming (deception, noise, spot, barrage) may be better or worse depending on the different circumstances. However, supposing that it has been decided that a noise jammer is what is needed, the question is, which noise jammer is most effective at producing noise at the output of the IF filter of the receiver. To answer this question, they consider field testing, simulations and mathematical analysis. They choose DINA as their baseline noise for the simple fact that DINA is white and gaussian. As was pointed out earlier in this thesis, DINA does not make the best use of the microwave amplifier in the noise jammer; however, it is white and

gaussian, and a simple I and Q analysis of the narrowband process coming out of the IF receiver with gaussian noise as its input will show that process to be gaussian also. It is not here *proved* that gaussian noise is optimal for noise jamming, but it is assumed.

When Benninghof and the rest turn their attention to FM/N as a jamming technique, they divide it into two categories: FM by wideband noise (FM/WBN) and FM by low frequency noise (FM/LFN). [1] The distinction between the two categories is based on the ratio of the bandwidth of the modulating noise to the bandwidth of the IF filter of the victim receiver, and this distinction is made because of the two distinct types of outputs of the victim receiver.

Even if the bandwidth of the RF spectrum of the FM/N signal is wider than, or at least as wide as, the bandwidth of the IF filter of the victim receiver, if the bandwidth of the *modulating noise* is smaller than the bandwidth of the receiver filter, this will result in an RF signal that moves slowly in and out of the passband of the receiver filter. Each time it moves into the receiver filter, it will "set the filter to ringing" or, in other words, produce a sinusoid at the output of the filter of limited time duration. If this signal is then applied to an envelope detector, the output will be a pulse of random shape, and duration equivalent to the time-constant of the IF filter (approximately the inverse of the bandwidth of the IF filter.) Over time, we should expect to see a series of these distinct pulses at the output of the envelope detector. This type of signal may be effective as a type of deception jamming, but it is not optimal as a noise jammer (in the sense of a masking jammer) and its statistics are non-gaussian.

On the other hand, if the bandwidth of the modulating noise is sufficiently wider than the bandwidth of the victim receiver's IF filter, the RF signal will quickly sweep back and forth through

[1] It should be noted here that this distinction is based on the ratio of the bandwidth of the modulating noise to the receiver bandwidth, while the distinction between NBFM/N and WBFM/N is based on the ratio of the bandwidth of the modulating noise to the frequency deviation of the FM modulator. Thus, in order to get an entire picture of the FM/N possibilities, we are forced to compare three separate bandwidths: the bandwidth of the modulating noise, the bandwidth of the RF spectrum of the FM/N signal, and the bandwidth of the victim receiver's IF filter, and we thus have four distinct categories: NBFM/LFN, NBFM/WBN, WBFM/LFN and WBFM/WBN. Practical noise jammers fall into the last category, but this thesis will consider, in Chapter 4, an analysis of the first category, (NBFM/LFN) and produce some interesting results concerning the time-statistics of such a signal.

the passband of the IF filter producing "overlapping pulses" at the output of the envelope detector. The signal resulting from this overlapping is the result of the addition of a number of random pulses, and the statistics of the signal is thus the convolution of the statistics of the individual pulses. (9) As this number increases, the Central Limit Theorem holds and the statistics of the signal become gaussian, giving precisely the same result as if the input to the victim receiver had been DINA rather than FM/N. This development leads Boyd to the following equation:

$$f_R < f_N < f_J \tag{6}$$

where f_R is the receiver bandwidth (we assume it to be the bandwidth of the IF filter of the receiver), f_N is the bandwidth of the baseband modulating noise and f_J is the bandwidth of the jamming barrage, i.e. the RF bandwidth of the FM/N signal (6:14–22).

Again, there is no proof that gaussianity is important in effective noise jamming, but this fact is assumed.

The question of the whiteness of the FM/N jamming spectrum is considered peripherally. No proof is given to show that a white spectrum is superior to a non-white spectrum, but a short derivation, taken from Middleton, is used to show how gaussian noise can be passed through a filter with an error function shape prior to being used to frequency modulate a carrier. This resulting RF spectrum is then uniform over a range. Such noise is called "erfer" noise because of the use of the error function (6:14–24). FM/S+N is also mentioned briefly at the end of this section as another way of whitening the spectrum of a broad FM/N barrage.

The next set of the papers of fundamental importance to the subject of noise quality in FM/N jamming comes from a series of classified experiments carried out by a team at Stanford Research Institute in the 1960's and 1970's. At least one of the technical reports from this time period has now been declassified (21) and an article based on that work was presented in *Electronic*

Warfare/Defense Electronics in 1977 f(30). This work has already been touched on in Chapter 2 of this thesis, so only the major points will be explored here.

Two distinct types of experiments were carried out by the SRI research team. The first used actual operational jammers and a sophisticated setup that allowed experienced radar scope operators to observe the signals displayed on A-scopes, B-scopes and PPI's and determine the presence or absence of real targets. Two things came out of this experiment: 1) The jammers which were most effective were separated from those which were less effective and 2) It was discovered that there was a very high correlation between gaussianity as measured by Turner noise quality and the J/S ratio required to produce a 50% probability of target detection (30).

The second type of experiments used a simulated jammer and a simulated radar receiver and merely measured the Turner noise quality of the signals produced by altering the different parameters of the simulated setup. The simulated jammer utilized a high quality baseband gaussian noise source feeding a voltage controlled oscillator with a bandwidth which was held constant. The baseband noise could be filtered to different bandwidths, allowing the jammer to operate in both WBFM/N and NBFM/N categories. Also, it was possible to add a sinusoid to the modulating noise, allowing the jammer to operate as an FM/S+N jammer. The simulated receiver had an adjustable IF bandwidth which could be made either broader or narrower than the baseband modulating noise, thus giving rise to either the FM/LFN or the FM/WBN cases, either with or without an added sinusoid. Concerning the case of FM/N when there is not an added sinusoid, only two conclusions are drawn about the various bandwidths:

$$B_{RF} \gg B_{IF} \tag{7}$$

and

$$B_m > B_{IF} \tag{8}$$

where B_m is the bandwidth of the modulating baseband noise (corresponding to Benninghof's f_N), B_{RF} is the the RF bandwidth of the FM/N signal (corresponding to Benninghof's f_J) and B_{IF} is the bandwidth of the IF filter of the victim receiver (corresponding to Benninghof's f_R.) If both these suggestions are followed *and* the RF bandwidth is several times greater than the modulating noise bandwidth (as would be logical), it is easy to see that the result will be WBFM/WBN. It should be noted that these requirements are a little more stringent than those offered by Benninghof, but still somewhat ambiguous. A third conclusion is offered concerning FM/S+N: if the sinusoidal waveform has a period with frequency greater than the IF filter bandwidth, the Central Limit Theorem can again be invoked and the result will be similar to the case of FM/N with an extended RF bandwidth.

The case of WBFM/LFN is considered and found wanting because the output of the envelope detector is a series of discrete random pulses rather than a continuous random wave. The pdf of the WBFM/LFN was found to be characterized by a delta function at zero volts (corresponding to the "dead" time between random pulses) and thus the noise quality was low (TNQ $\leq$ 4). When a Dicke fix receiver is used with an A-scope, it is found that the WBFM/LFN can be easily screened out and the real targets are not masked. However, a note is made that on a B-scope or a PPI, the WBFM/LFN is actually *more* effective than the WBFM/WBN because it produces a great multitude of false targets. However, this function might be better described as deception jamming than noise jamming, so this increase in performance does not indicate that the signal was more power efficient *as a noise jamming signal.*

It was difficult for the research team to explore the case of NBFM/N because the bandwidth of the modulating noise was limited to less than the bandwidth of a normal noise jamming barrage, and there was a desire to keep the bandwidth of the barrage constant; however, there were cases where the ratio of the RF bandwidth to the modulating bandwidth was as low as 1.5. If a ratio of 3 is taken as the arbitrary cut-off between WBFM and NBFM, then this could be considered NBFM/N.

It was noted that as the IF filter and RF FM/N bandwidths were held constant, the Turner noise quality decreased with increasing baseband modulating noise bandwidths, thus demonstrating that transitioning from the WBFM/WBN to the NBFM/WBN is something that should be avoided, although an explanation for this behavior is not offered. The NBFM/LFN was not apparently explored at all.

One last note should be made about these experiments. Although Turner states that the bandwidth of the baseband noise should be *greater* than the bandwidth of the IF filter of the victim receiver for FM/N, (and, indeed, the analysis leading to the application of the Central Limit Theorem would seem to require it) the following figure 3, taken from his own work, (30) indicates that a more accurate statement would be that the bandwidth of the modulating noise should be *comparable* to the bandwidth of the victim IF filter. In fact, it is seen that the maximum noise quality occurs when the modulating noise bandwidth is slightly less than the bandwidth of the IF filter (B_m = 5MHz, B_{IF} = 6.7MHz).

3.3 Tech Reports, Texts and Articles on EW

Several textbooks mention or allude to the noise produced by FM/N or FM/S+N jamming although the earlier references tend to be more obscure. ***Introduction to Radar Systems*** written by Skolnik in 1962 speaks briefly of "impulisive noise that can shock-excite the narrow-band radar receiver and cause it to ring," and he suggests the counter-countermeasure of the Dicke fix. Although he does not use the term "FM/N" there can be no doubt that this is what he has in mind, since the Dicke fix is not terribly effective against any other noise jamming scheme.

In 1983, the scene has changed somewhat, and Golden not only describes the function of the FM/S+N noise jammer in ***Radar Electronic Warfare***, but presents block diagrams and suggests parts to build your own noise jammer (11). He presents two ideas which are of interest here. The first is a brief explanation of why the FM noise jammer is preferable to DINA. Although DINA

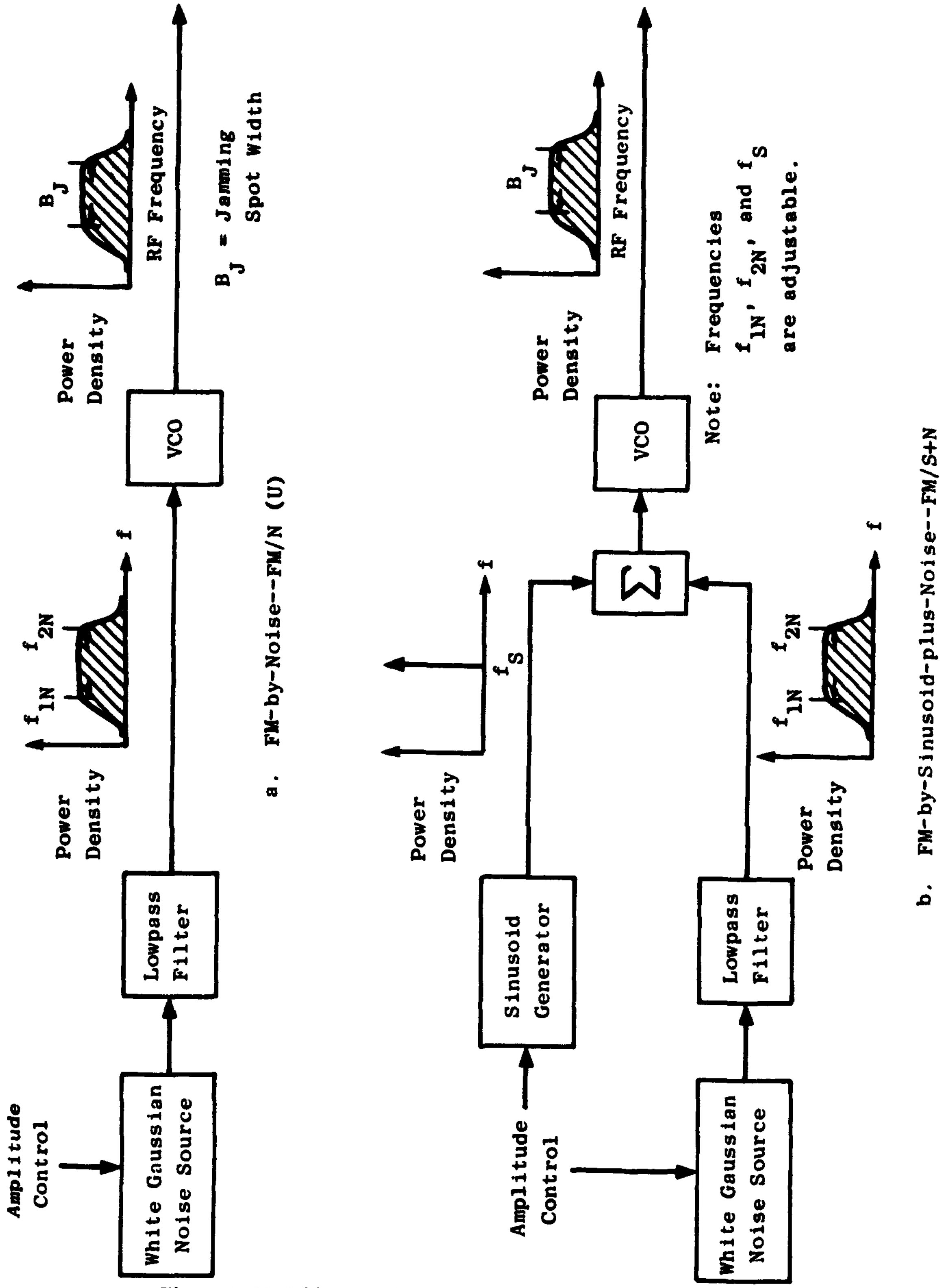


Figure 3. Variable Gaussian Test Source Calibration - FM/N

is much easier to analyze in its effects on the victim receiver, and its efficacy is less dependent on the relative parameters of the jammer and the victim receiver, the RF gaussian noise signal makes much less efficient use of the high powered microwave transmitter than does the FM signal. The amplitude of an RF gaussian noise signal is most often close to zero, but can theoretically be infinitely large, thus the microwave transmitter must operate at a fraction of its maximum power capacity most of the time or else clip the gaussian noise drastically, causing it to be non-gaussian. The FM jamming signal, on the other hand is at a more nearly roughly constant amplitude most of the time which allows it to take full advantage of the power capacities of the jammer transmitter.

The second idea is presented graphically in the figure reproduced here as Figure 4. Since the baseband signal FM modulates the jammer's carrier, it is valid to think of the top signal as being either the amplitude of the baseband signal with time *or* the frequency of the jammer signal with time. What is clear from the figure is that if the bandwidth of the RF jamming signal is much much greater than the bandwidth of the filter of the victim receiver, then the modulating noise will have to fluctuate more rapidly to produce constant ringing in the output of the victim receiver.

In 1985, Knorr and Dimitrios publish a paper describing work that exactly paralleled the work performed by the SRI research team, with the important exception that this work was done through computer simulation rather than laboratory simulation (14). The same tendencies were noted concerning FM/WBN, FM/LFN and FM/S+N. It is discovered that if the RF spectrum of the barrage is not centered on the victim receiver (so that the receiver picks up one of the "tails" of the barrage) the noise quality is reduced. In addition to sinusoids, periodic triangular and sawtooth waves are added to baseband noise and the results are found to be virtually identical to the FM/S+N case. Also, Knorr and Dimitrios offer their opinion that a noise quality of 10 or greater represents good noise quality.

In 1979, Cassara, Muth and Getty's publish a paper which proposes to apply the error function to gaussian noise prior to using it to frequency modulate a carrier in order to get a uniform RF

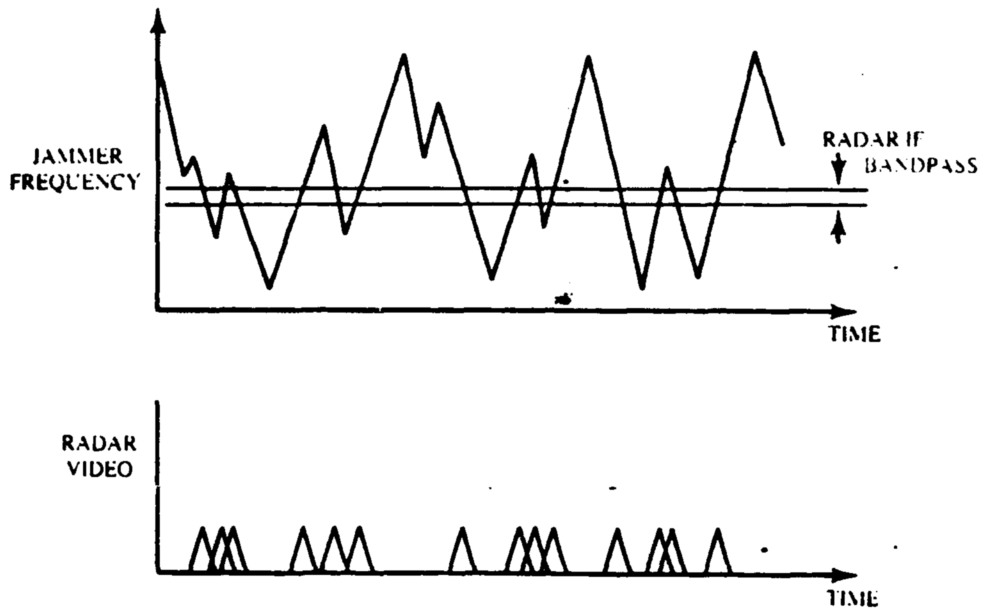


Figure 4. FM/S+N Effect on Radar Output

spectrum (7). Thomas Weil responds later in the same year explaining that the same idea had already been proposed by Middleton in 1955 (as had been noted by Benninghof) but was not subsequently employed because, essentially, the statistical characteristics of the RF signal were such that the output of the IF filter of the victim receiver was less gaussian (31). When one is forced to pick between gaussianity and whiteness in such a situation, it is found that while whiteness is more efficient at putting power into the passband of the victim receiver, the implication seems to be that the power that enters the receiver is not as efficient at masking the real targets.

Three other radar texts were investigated (19) (15) (10), but in each of these, all noise jamming was considered to be more or less equivalent. The J/S ratio was substituted into the radar range equations to demonstrate the effect of jamming, but the assumption in all cases was that the noise power entering the radar receiver was white and gaussian, while such is not the case, and, in fact noise jamming which deviates substantially from gaussianity has been shown to be far less effective at jamming than the amount of power delivered would indicate. From the standpoint of the radar

designer, this assumption will only lead to reasonable conservativeness, but there is a possibility that the radar jammer designer would overestimate the effectiveness of his jammer on the basis of these sorts of equations.

The most recent work of importance on the subject of FM/N is *An Analytical and Experimental Investigation of FM-By-Noise Jamming* written in 1992 (8). The primary emphasis of the research reported there was to thoroughly describe and demonstrate the FM/N effect. The relationships between the modulating noise bandwidth, the RF bandwidth of the FM/N signal, and the IF bandwidth of the victim receiver are analyzed more thoroughly than was done by Benninghof or the Stanford research team, and a new category: FM by unity bandwidth noise (FM/UBN) in addition to the categories of FM/LFN and FM/WBN, is suggested. The term refers to the relationship between the modulating noise bandwidth and the victim receiver bandwidth and it suggests that there may be some advantage to keeping these bandwidths reasonably close. This is a slight departure from the suggestion by Benninghof that the modulating noise bandwidth should be greater than the IF filter bandwidth, but it agrees with the experimental results produced by the SRI team.

Also a ratio called the sweep to victim ratio (SWR) is developed which quantifies the notion of a sweep rate: how often a noise signal is being swept across the frequencies of the victim IF filter. A criteria for determining the difference between a fast swept jammer and a slow swept jammer is then offered. This quantification is directly applicable only to an FM modulation scheme (it can be applied to FM/S+N as well with some modification) but it is, apparently, entirely new in the field of noise jamming or masking jamming.

The secondary emphasis of the research was the re-establishment of a technique for measuring noise quality on an operational jammer. Although this goal was not entirely achieved because of the limitations imposed by using only commercially available oscilloscopes and spectrum analyzers together with a fairly slow personal computer, it was demonstrated that Turner Noise quality could

be measured on a physical laboratory simulation. An important recommendation that came out of this secondary emphasis was the idea that a new standard of noise quality should be proposed that would measure the whiteness of the spectrum as well as the gaussianity of the univariate probability density. Two new measures were proposed which are mentioned in Chapter 2 of this thesis, examined theoretically in Chapter 4, and one of them was treated experimentally in Chapter 5.

The research reported in *An Analytical and Experimental Investigation of FM-By-Noise Jamming* (8) included two parts: 1) a theoretical investigation of FM/N which included some mathematical analysis and 2) the laboratory simulation which has been described earlier in Chapter 2. Other than the development of the SWR and the more rigorous analysis of the relationship between the three bandwidths which are fundamental to describing the FM/N behavior, there are no startling results in the mathematical analysis. When the experimental setup is considered, it is found to be similar in many respects to the setup used by the SRI team in that it produces noise of varying degrees of gaussianity at the output of the IF filter of a simulated victim receiver. It does not have an FM/S+N capability and it used only two different IF bandwidths. It duplicated the SRI result, showing an increase in gaussianity as the bandwidth of the baseband noise is increased from the WBFM/LFN to the WBFM/WBN case, but did not measure noise quality in either of the NBFM/N cases. In some respects it did less than the Stanford setup did, which is likely due to the amount of time and the cost and availability of equipment; however, what it accomplished which the Stanford setup failed to accomplish, was to produce a series of oscilloscope traces of baseband noise signals and corresponding IF filter outputs, which greatly facilitate an understanding of the FM/N behavior.

3.4 Summary

Although the articles, EW texts, technical reports and theses covered in this chapter have covered a lengthy span of time and represent a fair number of authors, it seems that with respect to the emphasis of this present thesis, two important concepts are consistently repeated. Firstly, it is always either assumed or stated that optimal noise for the purposes of noise jamming in the presence of a conventional receiver should have both a flat spectrum in the passband of the receiver being jammed and a gaussian first order probability density function as demanded by Shannon's work. Nonetheless, in the noise quality measure proposed by Turner, theoretically verified and apparently universally accepted by the EW community, the emphasis in quantitatively measuring noise quality is almost always focused on the gaussianity of the pdf rather than the flatness of the spectrum.

Secondly in the articles that deal with the shape of the FM/N spectra (Middleton, Stewart, Blachman, Abrahamson, Mullen, Turner) it is shown that the spectrum of the FM jamming signal generally conforms to Woodward's Theorem, provided that the peak frequency deviation of the modulator is sufficiently large, but becomes increasingly characterized as having a spike at the carrier frequency as the peak frequency deviation is decreased. Since Woodward's Theorem states that the shape of the RF spectra of a carrier frequency modulated by a baseband signal will take on the shape of the first order probability density of the baseband signal, under the situation of FM/N where the modulating noise is gaussian, this implies that under the best of circumstances, the FM/N spectrum will have a gaussian shape. This has been repeatedly proven and demonstrated by researchers in the area. Thus the FM/N spectra will never be perfectly flat over any bandwidth, and may in fact deviate quite a bit from ideal flatness.

That this realization caused some concern among researchers is indicated by the articles which deal with the investigation into erfer noise, a technique specifically designed to increase the flatness of the RF spectrum of an FM/N signal by changing characteristics of the baseband modulating

noise. The consensus seems to be that the increase in flatness obtained by erfing was not worth the loss of gaussianity which accompanied it; however, it is undeniable that increasing the flatness of the FM/N spectrum was seen as a desirable goal which was not perfectly attainable through the most common simple FM/N modulation scheme.

These two facts: the desirability of a noise signal in the receiver with a flat spectrum as well as a gaussian pdf, but a lack of quantitative measurement of the flatness of the received noise, coupled with the theoretical impossibility of perfectly flat noise when using a simple FM/N jamming scheme, seem to point to a need for defining a new standard of noise quality that quantitatively measures whiteness as well as gaussianity. Two such measures were proposed by Daly (8). These measures are considered theoretically in the next chapter, as well as a third measure proposed here for the first time, and all three measures are examined experimentally in the last three chapters.

IV. Theory of Noise Quality in FM/N

The problem of quantifying the properties of a jamming signal must deal with three components: 1) the analysis which shows a noise jamming signal of certain statistical characteristics to be ideal, 2) the analysis which shows what statistical characteristics a particular waveform generated in a particular way is likely to have and 3) the analysis which demonstrates how measurements of a particular jamming waveform may be used to estimate its statistical characteristics and reasonably compare them to the statistics of the ideal. In the particular case being discussed here, FM noise jamming, these three components are 1) demonstrating that ideal masking noise is gaussian in univariate probability density and appears white to the input of the victim receiver, 2) analyzing the theoretical whiteness and gaussianity of the four FM/N cases, and 3) showing the statistical validity of a proposed method for measuring whiteness and gaussianity.

4.1 Ideal Noise

There are two signal characteristics that are of primary importance for the purpose of determining the optimal noise jamming signal. The first is the "entropy" of the random process which characterizes the noise, and the second is the autocorrelation function of the random process. Entropy, in this context, is the concept introduced by Shannon, which is, precisely, a measure of the unpredictability of the random variables which compose the signal. A jamming signal with maximum entropy in a particular communication channel is optimally destructive of information in that channel (25) Entropy is defined as:

$$H(x) = -\int_{-\infty}^{\infty} p(x) \ln p(x) dx \tag{9}$$

where X is a continuous random variable and $p(x)$ is the probability density function of X.

Now, if the radar jamming signal is characterized by the random process $X(t)$, composed of random variables X, then the autocorrelation function of the random process shows how the value

of the random signal at one instant in time is related to the amplitude at any other instant in time and is defined as:

$$R_{xx}(t_1, t_2) = EX(t_1)X(t_2) \tag{10}$$

when X(t) is a real random process (23:122). If the value of the jamming signal at any given instant of time is completely unpredictable based on the knowledge of the signal at all other instances of time, this, again, is most destructive of information in any signal it is added to, and is likewise difficult to counter.

In order to avoid any confusion, it must be reiterated here that "destroying" information in a communication channel, in the sense of information destruction developed by Shannon, is not necessarily the best jamming technique. Often, deceptive jamming techniques which are less destructive of the desired signal than noise jamming would be are more effective at producing a specific desired jamming result. However, in terms of information destruction in a given channel, the signal with the highest entropy and the lowest correlation is optimal.

In the analysis that follows, the optimal autocorrelation function will be found first, and then that information will be used as a constraint on the maximizing of the entropy of the univariate pdf of the jamming signal.

4.1.1 Ideal spectral characteristics. First, it is important to note that $X(t)$ should be taken to be stationary. This simply means that the pdf's of the random variables composing X(t) are time invariant. As $H(x)$ is independent of any time variable, it obvious that the pdf found by maximizing H under any constraints will be found to be independent of time. Thus, for optimal jamming, we should use the signal with the maximum entropy for all time. Stationarity implies:

$$E\{X(t)\} = \mu_x = \text{a constant} \tag{11}$$

and

$$p(X(t)) = p(X(t+\tau), \tau \in (-\infty, \infty) \tag{12}$$

This then implies that

$$R_{xx}(t_1, t_2) = E\{X(t_1)X(t_2)\} = E\{X(t_1+\tau)X(t_2+\tau)\} \tag{13}$$

which implies that R_{xx} depends only on the difference between t_1 and t_2. If we let $\tau = |t_2 - t_1|$ then we can write:

$$R_{xx}(t_1, t_2) = R_{xx}(\tau) \tag{14}$$

If we now apply the criterion that $X(t)$ should be completely unpredictable based on knowledge of any other values of the jamming signal at any other times then we are implying that $X(t_1)$ is statistically independent of $X(t_2)$ for all $t_1 \neq t_2, t_1, t_2 \in (-\infty, \infty)$ which implies:

$$E\{X(t_1)X(t_2)\} = 0, t_1 \neq t_2, t_1, t_2 \in (-\infty, \infty) \tag{15}$$

which implies:

$$R_{xx}(\tau) = 0, \tau \neq 0 \tag{16}$$

This leaves us with two possible types of autocorrelation functions. The first is the function which is identically zero, but this will hardly serve as an optimal jamming signal, as it contains no power. The second is:

$$R_{xx} = \sigma^2 \delta(\tau) \tag{17}$$

where σ^2 is a constant, which is the autocorrelation function of the optimal jamming signal and will be denoted by $R^o_{xx}(\tau)$.

The Fourier transform of R_{xx} is known as the power spectral density function of $X(t)$ when $X(t)$ is stationary and is given by:

$$S_{xx}(f) = \int_{-\infty}^{\infty} R_{xx}(\tau) e^{-j2\pi f\tau} df \tag{18}$$

which is known as the Wiener-Khinchine relation. For optimal jamming:

$$S^{o}_{xx}(f) = \int_{-\infty}^{\infty} \sigma^2 \delta(\tau) e^{-j2\pi f\tau} df \tag{19}$$

$$S^{o}_{xx}(f) = \sigma^2 \tag{20}$$

which implies that our optimal jamming signal has equal power in all frequencies. This kind of signal is known as a white signal.

The average power in a stationary signal is given by:

$$E\{X^2(t)\} = R^{o}_{xx}(0) = \int_{-\infty}^{\infty} S^{o}_{xx}(f) df \tag{21}$$

$$E\{X_2(t)\} = \int_{-\infty}^{\infty} \sigma^2 df \tag{22}$$

which, unfortunately, is unbounded, implying that we should need to generate a signal with infinite average power. However, it will be later shown to be sufficient if the jamming signal merely *appears* white to the input of the IF filter of the victim receiver, a much less stringent condition. This condition of white "appearance" is not necessarily perfectly achievable, but at least it is not physically impossible.

Also note that for a white process, $E\{X(t)\} = \mu_x = 0$. This can be easily seen by observing that, for a stationary random signal, the mean of the signal corresponds to the dc, or zero frequency, power in the signal. The power over any range of frequencies of a stationary random signal may

be found merely by integrating the power spectral density over that range. Thus, to find the dc power of a white signal, we take:

$$P_{dc} = lim_{\epsilon \to 0} \int_{-\epsilon}^{\epsilon} S_{xx}^{*} \tag{23}$$

which goes to zero because of the absence of any delta function at $S_{xx}^{*}(0)$. This makes sense, intuitively. If the mean of a signal is *not* zero, then a constant (i.e. predictable) nonzero amount of its power must be located at dc and it therefore *cannot* be optimally unpredictable. In a white process, no energy is located at any discrete frequency.

4.1.2 Ideal probability density function. Now consider the entropy condition. In order to find the signal with the maximum entropy for a given signal energy, we must maximize $H(x)$ subject to the following constraints:

$$p(x) \geq 0, x \in (-\infty, \infty) \tag{24}$$

$$\int_{-\infty}^{\infty} p(x)dx = 1 \tag{25}$$

$$\mu_x = 0 \tag{26}$$

$$\int_{-\infty}^{\infty} x^2 p(x)dx = \sigma_x^2 \tag{27}$$

The constraints follow naturally from the fact that $p(x)$ is a pdf and therefore cannot be negative, must integrate to one and must have first and second moments. That the first moment is zero is a direct result from our contention that the optimal jamming signal be white.

At this point we will introduce two Lagrange multipliers to reduce the problem from one of finding a conditional maximum on $H(x)$ to one of finding an unconditional max on $H(p(x)) - \lambda\phi_1(p(x)) + \mu\phi_2(p(x))$ where ϕ_1 and ϕ_2 are the constraining functions arising from the fourth and second conditions. Thus we are to maximize I where:

$$I = \int_{-\infty}^{\infty} p(x)\ln p(x)dx - \lambda \int_{-\infty}^{\infty} x^2 p(x)dx + \mu \int_{-\infty}^{\infty} p(x)dx \tag{28}$$

$$= \int_{-\infty}^{\infty} p(x)[-\ln p(x) - \lambda x^2 + \mu]dx \tag{29}$$

Taking the partial derivative with respect to p and setting it equal to zero then yields:

$$-\ln p(x) - \frac{p(x)}{p(x)} - \lambda x^2 + \mu = 0 \tag{30}$$

which implies:

$$p(x) = e^{\lambda x^2 + \mu - 1} = e^{\mu - 1} e^{\lambda x^2} \tag{31}$$

substituting this expression back into the condition that $p(x)$ must integrate to unity, we have:

$$e^{\mu-1} \int_{-\infty}^{\infty} e^{-\lambda x^2} dx = 1 \tag{32}$$

which implies:

$$e^{\mu-1} = \sqrt{\frac{\lambda}{\pi}} \tag{33}$$

and then applying the constraint that σ_x^2 be the variance of $p(x)$, we have that

$$\lambda = \frac{1}{2\sigma_x^2} \tag{34}$$

Thus yielding:

$$p(x) = \frac{1}{\sqrt{2\pi}\sigma_x} e^{-\frac{x^2}{2\sigma_x^2}} \tag{35}$$

which is the familiar gaussian distribution.

The conclusion then, is that optimal noise, from the standpoint of destroying information in a channel, is characterized by *both* a white spectrum and a univariate probability density that is gaussian.

4.2 Theory of FM/N

4.2.1 Theory of FM. The concept behind frequency modulation of a carrier is intuitively simple. The idea is that the instantaneous frequency deviation of the carrier from its nominal frequency should be directly proportional to the amplitude of the modulating baseband signal. Mathematically, if the nominal frequency of the carrier is f_c, and the instantaneous frequency of the FM signal is f_i, then the instantaneous frequency deviation is:

$$\Delta f(t) = f_c - f_i(t) = f_d m(t) \tag{36}$$

which implies

$$f_i(t) = f_c + f_d m(t) \tag{37}$$

where f_d is some proportionality constant which will be referred to as the *frequency deviation constant* with units of Hz per volt, and $m(t)$ is the baseband modulating signal.

In general, the expression for any angle-modulated carrier can be written as:

$$v(t) = A\cos(\phi_i(t)) \tag{38}$$

where A is the amplitude of the signal and $\phi_i(t)$ is the instantaneous phase, usually of the form:

$$\phi_i(t) = 2\pi f_c t + \theta(t) \tag{39}$$

If we then use the fact that the instantaneous phase of an angle-modulated carrier signal is equal to the integral of the instantaneous frequency we can write:

$$\phi_i(t) = 2\pi \int_{-\infty}^{t} f_i(t)dt \tag{40}$$

which implies for the FM case:

$$v_{FM}(t) = A\cos(2\pi \int_{-\infty}^{t} f_i(t)dt) \tag{41}$$

and then, substituting,

$$v_{FM}(t) = A\cos(2\pi(f_c t + f_d \int_{-\infty}^{t} m(t)dt)). \tag{42}$$

which is the commonly found expression for FM.

Some terms associated with FM need to be defined. Now the theoretical spectrum of an ideal FM signal contains energy at frequencies which are potentially infinitely removed from the carrier frequency as the result of the fluctuating instantaneous frequency. Thus the width of the theoretical spectrum of the FM signal depends to some degree on the bandwidth of the modulating signal. If the bandwidth of the modulating signal increases, then fluctuations in the amplitude of the baseband signal, and hence, in the instantaneous frequency of the FM signal will increase. The increase in the rate of the fluctuations of the instanataneous frequency of the FM signal will result in a wider FM spectrum.

However, if the amplitude of the modulating signal is limited, this implies that the *instantaneous* frequency deviation of the carrier from its nominal value, f_c will be limited. Thus there will

be some maximum instantaneous frequency deviation attainable. This value will be consistently referred to as the peak frequency deviation and denoted Δf_p. In the case of a random modulating signal which is not necessarily bounded (and in the gaussian case is theoretically not bounded) it is sometimes more practical to speak of the rms frequency deviation denoted as: Δf_{rms}.

Even in the case where the random modulating signal $m(t)$ is unbounded, it is always assumed that it has a bandlimited spectrum which extends from around 0 Hz (not necessarily including any power at dc) up to some maximum frequency f_m. This implies that there is a bandwidth associated with $m(t)$ which we will denote as B_m and it will generally be assumed through the sequel that $B_m = f_m$ unless some other definition of bandwith is specifically referred to.

Typically the relationship between the spectral behavior of a baseband signal and the spectral behavior of the corresponding FM signal is spoken of in the FM literature in terms of the *modulation constant*, β, which is defined only for the case where a carrier is frequency modulated by a constant amplitude sinusoid. However, in the case of FM/N there is a greater direct application in using the terms developed above to introduce the concept of a *deviation ratio* D to compare the spectral behavior of the baseband noise to the spectral behavior of the FM signal when the modulating signal is arbitrary. The deviation ratio D is defined as:

$$D = \frac{\text{peak frequency deviation}}{\text{bandwidth of} m(t)} = \frac{\Delta f_p}{B_m} \tag{43}$$

4.2.2 Spectrum of FM/N. The preceding section laid the groundwork for the discussion of frequency modulation in the general case. When our attention turns to the spectrum of the FM signal, however, there are no general closed-form expressions that cover all situations, so the focus will be restricted primarily to the FM/N case from this point forward.

As has been noted several times in Chapter 3, the most common descriptions of the FM/N spectrum have employed Woodward's theorem in the WBFM/N case to approximate the RF spec-

trum as being gaussian, and have generally been complicated in any other case. A proof of Woodward's theorem can be found in Daly's thesis and it is applied to the WBFM case (8). That work will not be repeated here. Instead the approach developed by Abrahamson which covers the WBFM/N case, but which, more importantly, yields very nice results over the range of values where Woodward's theorem does not hold, which may or may not fall within a strict definition of NBFM/N will be considered here (1).

Rather than speaking in terms of the relationship between the size of the modulating bandwidth to the size of the FM/N bandwidth, as has been traditional, Abrahamson chooses to consider the rms value of the amplitude of the modulating signal (1). In order to appreciate the importance of Abrahamson's approach to the particular case of FM/N, it will be useful to contrast it with the traditional approach to the concept of bandwidth and spectra in FM.

Closed-form expressions for the FM spectrum cannot be found in general, but they can be found for particular special cases. A ubiquitous example, which will not be derived here, but which has done much to color thought on the notion of bandwidths and RF spectra, is that of a sinusoidal baseband modulating signal. When $m(t)$ is chosen to be a sinusoid, this gives rise to Bessel functions in the Fourier transform of the FM signal and thus a spectrum of delta functions (sometimes referred to as "sub-carriers") located at $f_c \pm nf_m$, where f_m is the frequency of the modulating sinusoid and n is a positive integer. If we restrict ourselves to looking only at the spectral lines which carry 90% or more of the power in the FM spectrum, we will find that the number of spectral lines which meet that criterion is directly related to average magnitude of the expression:

$$2\pi f_d \int_{-\infty}^{t} A \cos 2\pi f_m t \, dt \tag{44}$$

In other words, the number of spectral lines which contain a significant amount of power can be said to depend on the frequency deviation constant, *and* on the amplitude of the modulating signal.

The traditional approach is to focus on the frequency deviation constant. If f_d is very small, then we find that we have power in the carrier frequency, f_c, and in the first two spectral lines located at $f_c + f_m$ and $f_c - f_m$. Thus the bandwidth of the RF spectrum is roughly twice as wide as the bandwidth of the modulating signal, and, for low values of f_d, the RF bandwidth will increase with increasing baseband bandwidth as f_d is held constant. This condition is found to have some things in common with the large carrier AM spectrum (specifically, the size of the bandwidth and the fact that a large proportion of the energy of the signal is found at the carrier frequency) and is known as *narrowband FM* (NBFM).

However, as f_d increases, the FM signal deviates further in frequency from f_c and thus power is is no longer located at the carrier frequency but is pushed into additional spectral lines at the subcarrier frequencies. Thus for large f_d, the peak frequency deviation of the carrier may be many times the maximum frequency component found in the modulating signal $m(t)$, and thus the RF bandwidth will be found to depend more on f_d than on B_m. When this condition holds, this is known as *wideband FM* (WBFM) because the FM bandwidth is fairly wide in comparison to the baseband bandwidth.

Carson's rule, which is based on these kinds of general observations rather than specific theoretical considerations suggests that the bandwidth of an FM signal is:

$$B_{FM} = 2(D + 1)B_m \tag{45}$$

For large D, this expression becomes roughly $2DB_m$ or $2\Delta f_p$ (the approximation for WBFM). For D less than 1, this expression becomes roughly $2B_m$ (the NBFM approximation). It is obvious that in order for B_{FM} to be roughly equal to $2B_m$, D must be much less than 1. Which is on the same order as the bandwidth of the RF spectrum of an AM signal. As D is *much much* less than one, the FM signal will have many of the same characteristics as a large carrier AM signal in the time-domain as well as in the frequency-domain, and in the FM literature, a system referred to as

an NBFM system is a system characterized by a deviation ration much less than one. However, it is only necessary that D be on the order of 1 in order for the AM like spectral behavior to be present. And in the case of analyzing FM/N this spectral behavior which is significantly different from the WBFM/N spectral behavior is of the greatest significance. Thus, an FM/N system with a D as large as 2 will still be referred to as a NBFM/N system in this thesis.

In addition to Carson's rule, traditional FM analysis also refers to a null-to-null bandwidth, which may occur if there are distinct nulls in the RF spectrum, a 3 dB bandwidth (measured between the points where the magnitude of the spectrum falls 3dB below the peak magnitude) and a power bandwidth, based on the criterion that a certain high percentage of power be contained within the bandwidth.

For the purposes of an analysis of a sinusoid modulating signal, (such as might be used to transmit a baseband OOK signal at RF), or for the case where not much is known about the modulating signal other than its average power and its bandwidth, this preceding traditional analysis with the two categories of WBFM and NBFM is sufficient. However, when we know the precise spectral characteristics and the probability density function of the modulating noise we can find a much more precise characterization of the FM spectrum, particularly in the area which is neither precisely NBFM nor WBFM. Abrahamson does not develop a closed form expression in this intermediate range, but he does develop an analytical technique that allows the estimation of the FM/N spectrum to an arbitrary degree of accuracy with surprisingly little computation.

Going back to the example of the sinusoidal modulating signal, it is easy to see that if we talk about the amplitude of the modulating signal and assume a fixed frequency deviation constant, for some small amplitudes there will be only three spectral lines in the FM spectra ($B_{RF} = 2B_m$). However, as the amplitude increases, the frequency of the FM signal will deviate further and further from f_c, yielding a wider spectrum.

If we depart from the sinusoidal modulation case and consider the case where the baseband modulation is some bandlimited white gaussian process, then we have a roughly analogous situation. The gaussian process can take on *any* value from $-\infty$ to ∞; however, based on its variance or, to put it another way, based on the power in the process, there is a mean square value which gives an indication, on the average, of what its amplitude will be limited to. Thus for very low rms values of the modulating signal, the bandwidth of the FM spectrum will be roughly the same size as the the baseband bandwidth shifted in frequency ($B_{RF} = 2B_m$). However, as the rms value of the modulation signal increases, the FM signal will deviate further and further from f_c, on the average, until, at some point, the bandwidth of the FM spectrum will be independent of B_m.

This fact leads Abrahamson to define an rms bandwidth, which has particular significance when speaking of random signals:

$$B_{FM_{rms}} = \frac{1}{2\pi} P_m \tag{46}$$

where P_m is the rms amplitude of the modulating signal $m(t)$. Abrahamson's comment on this result is significant: (1:408)

> Note that in the FM case, the rms bandwidth of the modulated wave does not depend upon the bandwidth of the modulating wave, but only upon its rms value.

It will be helpful at this point to introduce the rest of Abrahamson's notation. As noted above P_m is used to denote the rms value of the modulating signal. In general, Abrahamson uses P^2 is used to denote the mean square value of a random process, i.e:

$$P^2 = R(0) = \int_{-\infty}^{\infty} S(f)df \tag{47}$$

where $R(\tau)$ is the autocorrelation and $S(f)$ the spectrum of the random process, and the usual Fourier transform relationship links them (1):

$$S(f) = \int_{-\infty}^{\infty} R(\tau)e^{-j\omega\tau}d\tau \tag{48}$$

and

$$R(\tau) = \int_{-\infty}^{\infty} S(f) e^{j\omega\tau} df \tag{49}$$

where

$$\omega = 2\pi f.$$

R and S may be normalized to yield $\rho(\tau)$ and $\sigma(\tau)$:

$$\rho(\tau) = \frac{R(\tau)}{P^2} \tag{50}$$

and

$$\sigma(f) = \frac{S(f)}{P^2} \tag{51}$$

It follows directly that $\rho(\tau)$ and $\sigma(f)$ also form a Fourier transform pair. Also note that the spectral density, $\sigma(f)$ is a non-negative function of unit area, and thus has the properties required of a probability density function.

Furthermore, if $\rho(\tau)$ is the normalized autocorrelation of some bandlimited process centered around a frequency f_c, then it makes sense to talk about the baseband autocorrelation $\rho_0(\tau)$ where:

$$\rho(\tau) = \rho_0(\tau) \cos 2\pi f_c \tag{52}$$

and it is well known that the principle of heterodyning insures the bandlimited spectrum corresponding to $\rho(\tau)$ is merely the spectrum of the baseband process shifted to center around $\pm f_c$:

$$\sigma(f) = \frac{1}{2}[\sigma_0(f - f_c) + \sigma_0(f + f_c)] \tag{53}$$

Now, to solve for the statistical form of the spectrum, we will find the Fourier transform of the autocorrelation function of the FM signal. If we define the FM signal to be $v_{FM}(t)$, as before, and let

$x(t)$ represent the angle modulation caused by our message signal $m(t)$ (i.e. $x(t) = 2\pi f_d \int^t m(t)dt$) then the autocorrelation function, $R_v(\tau)$ of the FM signal has been found to be: (17)

$$R_v(\tau) = \frac{A^2}{2} e^{-R_x(0)} e^{R_x(\tau)} \cos 2\pi f_c \tau \tag{54}$$

and there is a Fourier transform relationship between $R_v(\tau)$ and the spectrum of $v_{FM}(t)$, $S_v(f)$.

If we now replace $R_v(\tau)$ by the normalized autocorrelation function $\rho_v(\tau)$ and let $A = 1$ we have:

$$\rho_v(\tau) = e^{-P_x^2 \rho_x(0)^2} e^{-P_x^2 \rho_x(\tau)} \cos 2\pi f_c \tau$$

$$\rightarrow \rho_v(\tau) = e^{-P_x^2} e^{-P_x^2 \rho_x(\tau)} \cos 2\pi f_c \tau \tag{55}$$

The baseband autocorrelation function associated with the FM signal is then (by eq 52):

$$\rho_{v0}(\tau) = e^{-P_x^2} e^{-P_x^2 \rho_x(\tau)}. \tag{56}$$

We can now make use of the series expansion for the exponential to obtain:

$$\rho_{v0}(\tau) = e^{-P_x^2} \left[1 + P_x^2 \rho_v(\tau) + \frac{P_x^4}{2!} \rho_x^2(\tau) + \frac{P_x^6}{2!} \rho_x^3(\tau) + \cdots \right] \tag{57}$$

And, if P_x^2 is finite, we may tranform eqn 57 term by term to obtain the baseband normalized spectrum $\sigma_{v0}(f)$. Note that the transform of $\rho^2(\tau)$ is merely the convolution of $\sigma(f)$ with itself, and similarly, for $\rho^3(\tau)$, we have $\sigma(f) \overset{3}{*} \sigma(f)$ indicating the double convolution of $\sigma * \sigma * \sigma$:

$$\sigma_{v0}(f) = e^{-P_x^2} \left[\delta(f) + P_x^2 \sigma_x(f) + \frac{P_x^4}{2!} \sigma_x(f) * \sigma_x(f) + \frac{P_x^6}{2!} \sigma_x(f) \overset{3}{*} \sigma_x(f) + \cdots \right] \tag{58}$$

An expansion similar to this was found in Middleton's work (cited in Chapter 2) so Abrahamson refers to eqn 58 as the Middleton expansion; however, Middleton did not express it in a

form that could be easily used to calculate the FM/N spectrum. If we return to the case where our modulating signal $m(t)$ is a bandlimited white gaussian process, with maximum frequency f_m, then it is readily apparent that $\sigma_x(f)$ is a rect function with unit area in the frequency domain, extending from $-f_m$ to f_m. The first convolution of $\sigma_x(f)$ with itself will give rise to a tri function, also with unit area, extending from $-2f_m$ to $2f_m$. And the double convolution and all higher convolutions will give rise to functions that are very nearly gaussian for all practical purposes, with increasing variances.

Thus, the FM/N spectrum will look (excluding the small amount of power present in a spectral line at f_c) like a constant, multiplied by a rect of bandwidth $2B_m$, plus a tri of bandwidth $4B_m$, plus a number of bell shaped curves of bandwidths $6B_m, 8B_m, \ldots$. When P_x is much less than 1, its higher powers (P_x^2) will be very small and the rect function will dominate, giving us an FM/N bandwidth of roughly $2B_m$. As P_x increases to 1, the tri function will become larger, giving us a pointed, but still narrow, spectrum. As P_x becomes much larger than one, the gaussian-like terms will dominate giving the overall appearance of a gaussian spectrum, actually becoming gaussian in the limit.

It is important to remember that P_x is a measure of both the frequency deviation *and* the power present in the modulating signal, thus it can be increased either by amplifying the baseband modulating signal or by increasing f_d.

The parameter which could most easily be controlled in the experiments demonstrating the various types of FM/N was the peak frequency deviation, therefore it was desirable to develop an expression relating P_x to Δf_p. This has no theoretical significance, but is useful for relating the shape of the spectrum shown on the frequency analyzer to the shape of the spectrum predicted by Abrahamson's analysis.

Stewart has shown that for wideband FM:

$$B_{WBFM} = \Delta f_{rms}(8 \ln 2)^{\frac{1}{2}} \tag{59}$$

which, for values of $P_x > 1$ is equivalent to the result of 46. I.e.:

$$B_{WBFM} = \frac{1}{2\pi} P_x \tag{60}$$

Now it is known that for a gaussian process, less than 99% of the samples of the process will have amplitudes exceeding three times the standard deviation. Therefore, if the rms value of the modulating signal causes a frequency deviation Δf_{rms} then the peak frequency deviation is likely to be no greater than

$$\Delta f_p = 3\Delta f_{rms} \tag{61}$$

which implies:

$$P_x = \Delta f_p \frac{2\pi\sqrt{8 \ln 2}}{3} \tag{62}$$

Additionally, we can find an expression for D in terms of B_m:

$$D = \frac{3}{2\pi\sqrt{8 \ln 2}} \frac{P_x}{B_m} \tag{63}$$

4.2.3 Behavior of FM/N Jamming. At this point, the discussion turns to the effects of receiving an FM/N signal, specifically to what the output of the IF filter of the victim receiver will look like. Having obtained a spectrum for the FM/N signal, for both NBFM/N and WBFM/N, it is easy to find the spectrum for the output of the IF filter of the victim receiver if we know the IF frequency and the transfer function of the filter. Since we know that the RF FM/N spectrum will

be a bandpass process, we can write it as:

$$S_{FM}(f) = \frac{1}{2}[S_b(f - f_c) + S_b(f + f_c)] \tag{64}$$

where $S_b(f)$ is the unnormalized baseband version of the spectrum as found in the previous section (it is merely $\sigma_s(f)$ scaled by a constant.) Similarly the transfer function of an IF bandpass filter centered at some frequency f_{IF} can be written as

$$H_{IF}(f) = [H_b(f - f_i) + H_b(f + f_i)] \tag{65}$$

If we assume that the FM spectrum is centered on the receiving band of the victim receiver, and that the victim receiver employs the principle of heterodyning to bring the signal at f_c down to f_i, then it is obvious that the spectrum at the output of the IF filter can be written as:

$$S_{IF}(f) = \frac{1}{2}[(H_bS_b)(f - f_i) + (H_bS_b)(f + f_i)] \tag{66}$$

Since we have shown in section 4.1 earlier in this chapter that ideal noise has a white spectrum, it is obvious that if the input to the victim receiver is ideal noise, then the output of the IF filter of the receiver will have a spectrum that precisely matches the transfer function of the IF filter. Furthermore, if the input to the victim receiver is *bandlimited* white noise centered on the victim receiver, with a bandwidth wider than the bandwidth of the IF filter, the output of the filter will be precisely the same. Thus it is shown that ideal noise *with respect to a particular victim receiver* need not be absolutely white, but merely white in the passband of the victim receiver.

Using the terminology introduced in Chapter 3, it is possible to examine four different possible FM/N jamming schemes in terms of the required whiteness. If a WBFM/N jamming scheme is used, then the shape of the RF spectrum will be gaussian. If a relatively small central portion of

this spectrum is intercepted by the IF filter of the victim receiver, then the output of the IF filter will roughly approximate the shape of the IF filter, giving a result similar to that of a purely white noise input. If it is also true that the bandwidth of the modulating noise is as wide or wider than the bandwidth of the victim receiver, then this condition is known as WBFM/WBN, and it is nearly optimal from the standpoint of the spectral analysis. If the bandwidth of the noise is *not* quite as wide as the bandwidth of the IF filter (for example, B_m = 100 kHz, D = 10 implies B_{RF} = 1 MHz, but B_{IF} = 200 kHz) then the radar is operating as a WBFM/LFN jammer. From the standpoint of analysis of the magnitude of the spectrum alone, this situation is exactly equivalent to WBFM/WBN.

If, on the other hand, the RF spectrum is narrower than the bandwidth of the IF filter, then the output of the IF filter will contain a bell-shaped hump at the center frequency, but will be largely untouched at higher and lower frequencies. It can be reasonably deduced that this is the WBFM/LFN condition because we know that in WBFM the RF bandwidth of the signal is much wider than the bandwidth of the modulating noise, thus, if the RF bandwidth of the WBFM/N signal is narrower than the bandwidth of the victim receiver, then it follows directly that the bandwidth of the modulating noise is much smaller than the bandwidth of the victim receiver. This situation is highly undesirable from the standpoint of masking jamming, because it allows the operator of the victim receiver unrestricted use (from a theoretical standpoint) of those higher and lower frequencies.

It is this analysis, based on the assumption of WBFM, which leads us to the recommendation made by Turner and others that in FM/N jamming, the RF bandwidth of the FM/N signal should be much much larger than the IF bandwidth of the victim receiver.

If a NBFM/N jamming scheme is assumed, we have two other possibilities, neither of which are very desirable. If, again, the RF spectrum of the jamming signal substantially wider than the bandwidth of the victim receiver, then only a small central portion of the RF spectrum will

be intercepted, and the output of the IF filter will be the product of the RF spectrum and the transfer function of the filter. This condition is most likely NBFM/WBN because we know that the RF bandwidth of the NBFM signal is very well approximated by $2B_m$. Thus, if a NBFM system produces a signal substantially wider than the baseband bandwidth of the victim receiver, unless the three bandwidths are very closely matched, it is likely that the modulating noise has a bandwidth as wide or wider than the bandwidth of the victim receiver. The important characteristics of the output signal are that in all NBFM cases, more power is concentrated at the center frequency of the spectrum than at the edges by comparison to the WBFM case. This is not necessarily easily countered by signal processing in the victim receiver, but it is, theoretically, less than optimum. This situation, on the basis of spectral analysis alone, would seem to be better than the WBFM/LFN when the RF bandwidth is narrower than the bandwidth of the victim receiver because it at least puts *some* noise power in all frequencies used by the victim receiver.

If NBFM/N jamming is used and the RF bandwidth is substantially smaller than the bandwidth of the victim receiver, it can easily be seen that this condition must be NBFM/LFN. If we again approximate the NBFM/N RF bandwidth as $2B_m$, then a victim receiver IF bandwidth greater than the RF bandwidth directly implies an IF bandwidth at least twice as wide as the bandwidth of the modulating noise. From the standpoint of spectral analysis, this situation suffers from being less than ideal in the same sense as does the WBFM/LFN case mentioned above.

However, as has been constantly reiterated in this thesis, the spectrum of the noise (in the sense of the magnitude of the spectrum) is only half the equation. The other half is the probability density of the output of the IF filter of the victim receiver. Determining the theoretical probability density is far more complicated than determining the theoretical spectrum of the FM/N signal either at RF or after being passed through a filter. Nonetheless, a few general observations can be made.

Referring to figure 5 we see the baseband modulating voltage passing through a voltage range. As it does so, the FM/N signal passes through a corresponding range of frequencies. A range of these frequencies correspond to the frequencies in the pass band of the IF filter of the victim receiver. As the modulating noise enters these frequencies, a narrowband response is generated at the output of the IF filter which has some characteristics of linear FM in frequency, a random envelope, and a duration that is the greater of the the time the baseband signal lingers in the IF pass band, and the time constant of the filter. (The time constant of the filter is approximately $1/B_{IF}$.)

If the modulating noise is bandlimited white gaussian noise limited to some maximum frequency B_m, then it will have a zero crossing about once every $1/B_m$ seconds on the average. Again, assuming that the RF spectrum of the FM/N signal is centered on the passband of the victim receiver, this implies that the FM/N signal will sweep through the passband of the victim receiver about once every $1/B_m$ seconds.

If the bandwidth of the modulating noise is greater than the bandwidth of the IF filter of the victim receiver, this implies that, on the average, the filter's response to one noise sweep will not be over before the next sweep occurs; thus the responses will overlap and there will generally always be a consistent amount of total power at the output of the IF filter. If the bandwidth of the modulating noise is equal to the bandwidth of the IF filter, the response from one sweep will be ending just as the next one begins, with the consequence that there will probably be some small gaps left between responses. If the bandwidth of the modulating noise is less than the bandwidth of the IF filter of the victim receiver, there will definitely be gaps between one response and the next, of average duration $1/B_m - 1/B_{IF}$.

When the pulses overlap, it has been contended by almost all the authors who have written on the subject (20) (6:14) (21) that it is not necessary to know the probability distribution of any of the individual filter responses: the univariate probability density of the total waveform can be found

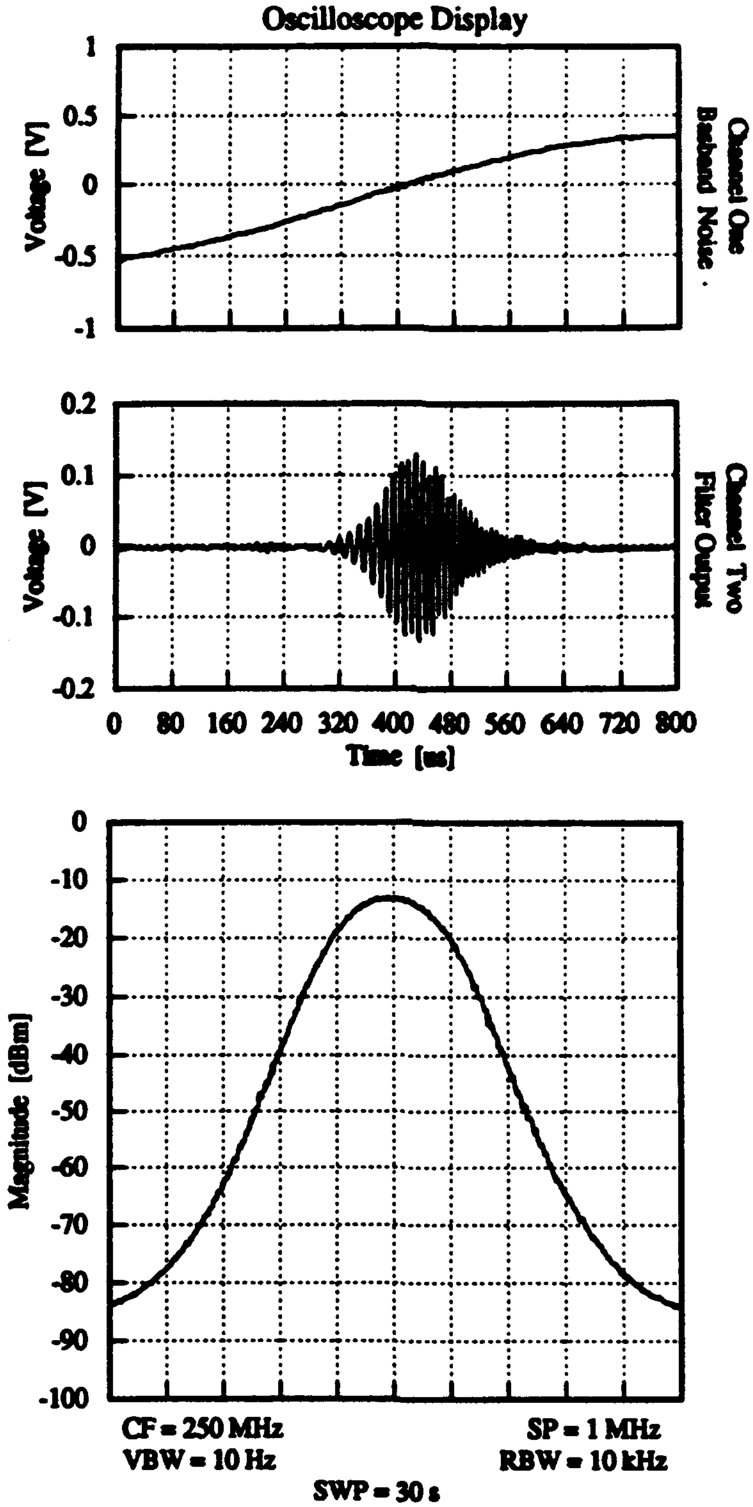


Figure 5. Baseband noise, RF spectrum and IF output for WBFM/LFN (8:4)

to be gaussian merely by observing that the total waveform is the sum of the individual pulses, the sum of a number of random variables has a pdf which is the convolution of their individual pdfs, and if you convolve *any* pdf enough times you will obtain a gaussian pdf. This general concept is presented explicitly as the Central Limit Theorem, which holds when the random variables are independent and have pdfs which are bounded.

This line of reasoning might lead one to conclude, falsely, that the pdf of the output of the IF filter of the victim receiver would be gaussian even when the pulses do not overlap. However, if there are dead spaces between filter responses and samples are taken during those dead spaces, the correlation between one sample and the next is likely to be very high. Thus the Central Limit Theorem fails because of the lack of independence between samples. Likewise there is a failure of the Central Limit theorem when NBFM/N is employed. Because of the predominance of power at f_c in the NBFM/N signal, the response of the filter tends to look more like a sinusoid at the central frequency plus gaussian noise, rather than purely gaussian noise.

Again, it will be useful to look qualitatively at the characteristics of the probability density functions associated with each of the four possible FM/N jamming schemes.

When WBFM/WBN jamming is employed, we are now virtually guaranteed that the Central Limit Theorem will hold and that the output of the IF filter of the victim receiver will be gaussian. There will be no dead spaces between filter responses, nor will there be any carrier frequency component. This noise should have the same quality as DINA noise, in a univariate statistical sense, and the fact that it seemed to do as well as DINA experimentally is what led Turner, Ottoboni and others to suggest that $B_{IF} < B_m$.

WBFM/LFN is obviously less gaussian than WBFM/WBN. Even if the RF bandwidth of the WBFM/LFN is wide enough to cover the bandwidth of the victim receiver with fairly white noise, there will be gaps between one filter response and the next and the univariate pdf of the output

of the IF filter will have a delta function at zero volts, indicating the certain probability that the signal will take on the value of zero for a certain percentage of the time.

NBFM/WBN is also less gaussian than WBFM/WBN, although it is more gaussian than WBFM/LFN. It has rapid enough sweeps through the pass band of the IF filter that there is a consistent noise power generated at the output of the IF filter; however, the presence of the carrier invalidates the application of the Central Limit Theorem, and the pdf of the output of the IF filter will tend to be "fatter" than a gaussian pdf. As is well known, the pdf of a pure sinusoid is given by:

$$p_{\sin}(x) = \frac{1}{\sqrt{1 - (x/\Delta x)^2}} \tag{67}$$

where Δx is the maximum (and $-\Delta x$ is the minimum) value taken on by the sinusoid. This function is characterized by two sharp peaks: one each at Δx and $-\Delta x$. When this kind of function is combined with an essentially gaussian function where the gaussian function dominates, the result is to make the gaussian function more "wide-shouldered": flatter across the top and more steeply descending down the sides.

Lastly, consider the NBFM/LFN case. It might be supposed at first that the signal at the output of the IF filter would suffer from "dead spaces" on a regular basis, but in the case of true NBFM, this is not so. The entire frequency excursion of the RF signal is either less than or on the order of the bandwidth of the IF filter, thus the RF signal is always causing a response in the IF filter of the receiver. A true NBFM/LFN signal will mainly resemble nothing so much as AM/N; that is, it will look much like a single frequency with a randomly modulated envelope. The pdf then looks much like the pdf of a sinusoid.

However, if one starts with a WBFM/LFN system (which is characterized in the time domain by these "dead spaces", and in pdf by the delta function at zero) and, rather than increasing the baseband noise, begins *decreasing* the peak frequency deviation of the FM modulator, thus moving away from WBFM/LFN and toward NBFM/LFN, two things will happen: 1) the dead spaces

will become shorter, and some will disappear, because the RF signal is not wandering out of the passband of the victim receiver so often, and 2) the "wide-shoulderedness" of the excess carrier will bring up the rest of the pdf. Thus, when the two problems one commonly encounters in FM/N are carefully combined in moderation, a few dead spaces combined with a slightly wideshouldered function, can, ironically, give the appearance of a more gaussian pdf than that obtained from either NBFM/WBN or WBFM/LFN. This fact demonstrates one of the problems with trying to measure the quality of a noise signal using only univariate statistical data, since a whiteness test would certainly screen out this kind of pathological behavior.

To summarize the mostly qualitative discussion of the effects at IF of the various FM/N jamming schemes, it is asserted here that: 1) the FM/N jammer should operate in a WBFM mode in order to insure a spectrum that is as "white" as can be achieved, and 2) the FM/N jammer should have a modulating noise bandwidth that is at least as wide as the bandwidth of the IF filter of the victim receiver. In other words, (using Stewart's criterion for WBFM (26):

$$D = \frac{\Delta f_p}{B_m} > 2.253 \tag{68}$$

and

$$B_m \geq B_{IF} \tag{69}$$

If we substitute $B_m = B_{IF}$, and $\Delta f_p = 2.253 B_m$ into the equation for the 3 db bandwidth of the WBFM signal (equation 59), we obtain:

$$B_{WBFM} = .751 B_m \sqrt{8 \ln 2} = 1.768 B_m = 1.768 B_{IF} \tag{70}$$

It is obvious that the 3 dB bandwidth of the FM/N signal will be somewhat wider than the bandwidth of the victim receiver, and this implies that some jamming power will be "wasted" in that it is being broadcast, but will not be received by the victim receiver. However, it is contended

that this is the absolute minimum bandwidth that can be broadcast and still be an optimal FM/N jamming signal in terms of not having significant "dead spaces" in between filter responses as a result of FM/LFN, and not having a wideshouldered (i.e. non-gaussian) univariate pdf because of the typical NBFM/N excess carrier power.

To complete the description of the behavior of FM/N, some terms associated with the concept of a "sweep rate" should be explained. Benninghof *et. al.*(6:14) introduce the concept of a "fast swept" as opposed to a "slow swept" signal by talking about the sweep rate of a linearly swept signal

$$v_i(t) = A_1 \cos\left(\frac{St^2}{2}\right) \tag{71}$$

moving with increasing frequency through the pass band of a gaussian filter with transfer function:

$$H(\omega) = A^2 \exp\left[\frac{-(\omega - \omega_o)}{2b^2}\right] \tag{72}$$

and they define a ratio a where:

$$a = \frac{S}{b^2}. \tag{73}$$

It is obvious that as a increases, the signal will "sweep through" the frequencies passed by the filter more rapidly. An FM/N signal which sweeps too slowly is likely to have the "dead spaces" characteristic of FM/LFN. Avoiding this problem is as simple as adhering to the criteria already given above that $B_{IF} \leq B_m$; however, it is possible to calculate a statistical sweep speed for an FM/N system and place appropriate constraints on it, and Daly has done so (8:3-10). He defines two ratios that get to the heart of the FM/N issue, the *noise-to-victim* ratio (NVR) which is defined as:

$$\text{NVR} = \frac{\text{bandwidth of baseband noise}}{\text{bandwidth of victim receiver}} = \frac{B_m}{B_{IF}} \tag{74}$$

and the *deviation-to-victim* ratio (DVR) which is defined as:

$$\text{DVR} = \frac{\text{peak frequency deviation}}{\text{bandwidth of victim receiver}} = \frac{\Delta f_p}{B_{IF}} \tag{75}$$

The NVR determines whether the FM/N jamming scheme is FM/WBN or FM/LFN, while the DVR determines whether or not the pass band of the victim receiver is being completely jammed.

He then defines a third ratio, based on the previous two, the *sweep-to-victim* ratio (SWR) defined as

$$\text{SVR} = \text{NVR} \cdot \text{DVR} = \frac{B_m \Delta f_p}{B_{IF}^2} \tag{76}$$

which indicates how often a noise pulse will be generated in the victim receiver and how long the baseband modulating noise will linger in the IF pass band, on the average. As Daly points out, an FM/N system cannot operate efficiently if it has an SVR below a certain threshold (it is suggested in this thesis that NVR can be no less than 1 and DVR can be no less than 2.253, thus the SVR can be no less than 2.253); however, an SVR higher than any given threshold does not necessarily insure the proper functioning of the FM/N scheme. The NVR and the DVR must be mixed in the proper proportions.

4.3 Measuring Noise Quality

Knowing what kind of noise is ideal and what kind of noise an FM/N system reliably produces, in general terms, the question arises, how can the superiority of one noise source to another be *quantitatively* determined? So far three suggestions have been offered (30) (8). Two of them will be examined here from a theoretical standpoint, and a fourth one, which perhaps combines some of the best aspects of the preceding measures, will also be offered.

4.3.1 Turner Noise Quality. Turner noise quality, briefly defined in Chapter 2, is based on the similarity between the properties of a histogram of samples of the output of the IF filter

and the corresponding properties of the univariate pdf of a theoretical gaussian noise signal. The group at Stanford which produced the initial noise quality measurements and formulated Turner noise quality formed a histogram using on the order of 1 million to 5 million samples while Daly's implementation of Turner noise quality used only on the order of 1000 to 10000 samples. Again, the Stanford group sorted sample points into either 512 or 1024 voltage bins, while Daly used voltage bin widths of 0.2σ, where σ is the standard deviation, which typically generated 30 voltage bins. (If we find maximums at around $+3\sigma$, and minimums at around -3σ as expected, then $+3\sigma - (-3\sigma)/0.2\sigma = 30$) These details aside, once the samples were processed and sorted into voltage bins, the error measures used were consistent.

Assuming N samples $v_i, i = 1, 2, \ldots N$, and K voltage bins, where N, K are positive integers, the number of samples in the ith bin can be denoted as $p_s[i]$. If the mean and variance of the samples are computed as:

$$\mu_v = \frac{1}{N}\sum_{i=1}^{N} v_i \tag{77}$$

and

$$\sigma_v^2 = \frac{1}{N^2}\sum_{i=1}^{N}(\mu_v - v_i)^2 \tag{78}$$

then the number of samples associated with the ith bin predicted by the ideal gaussian distribution can be easily estimated as:

$$p_g[i] = N\Delta v \frac{1}{2\pi} e^{\frac{(\mu_v - \hat{v}_i)^2}{2\sigma_v^2}} \tag{79}$$

where Δv is the bin width and $\hat{v}_i$ is the average voltage associated with the ith voltage bin found as:

$$\hat{v}_i = \frac{1}{2} i\Delta v - v_{min} \tag{80}$$

where v_{min} is the minimum voltage chosen to be -3σ.

Three error terms are computed by directly comparing $p_s[i]$ with $p_g[i]$. The summed error e_s is simply:

$$e_s = \frac{1}{N} \sum_{i=1}^{K} |p_g[i] - p_s[i]|. \tag{81}$$

The rms error e_r is found as:

$$e_r = \left[\frac{1}{K} \sum_{i=1}^{K} \left(\frac{p_g[i] - p_s[i]}{p_g[i]} \right)^2 \right]^{1/2}. \tag{82}$$

And the average error e_a is found as:

$$e_a = \left[\frac{1}{K} \sum_{i=1}^{K} \frac{|p_g[i] - p_s[i]|}{pi_i} \right]. \tag{83}$$

Three other measures of the sample histogram are computed and compared to the ideal gaussian. The relative entropy in bits H_b is the absolute value of the difference between the entropy of the sample histogram and the ideal entropy of a gaussian with the same variance, calculated as:

$$H_b = \sum_{i=1}^{K} \frac{p_s[i]}{N} \cdot \ln_2 \left(\frac{ps_s[i]}{N} \right) + \ln_2(\sigma_v \sqrt{2\pi e}). \tag{84}$$

The kurtosis, k is found as:

$$k = \frac{1}{N\sigma_v^3} \sum_{i=1}^{K} (\mu_v - i)^3 p_s[i]. \tag{85}$$

and the skewness s is, similarly:

$$s = \frac{1}{N\sigma_v^4} \sum_{i=1}^{K} (\mu_v - i)^4 p_s[i]. \tag{86}$$

It is known that as a sampled function has a univariate probability density function approaching the ideal gaussian pdf, the three error measures will become increasingly small, the relative entropy will approach zero, the kurtosis will approach a value of 3, and the skewness (which gives

an indication of the symmetry of the pdf) will approach zero. Turner noise quality combines these measures in an ad hoc manner as:

$$\frac{1}{\text{TNQ}} = \frac{1}{3} \cdot \left[\frac{e + a + e_r + e_s}{3} + \frac{|k - 3| + s}{2} + |H_b| \right] \tag{87}$$

and it is easy to see that as the gaussianity of the curve increases, Turner noise quality will increase without bound. Turner indicates that high quality baseband video noise sources in the laboratory have noise qualities ranging from 10 to 70, and he suggests that a TNQ of 4 is acceptable in jamming applications (30).

The team at Stanford indicated that the whiteness of a noise jammer, in the passband of the victim receiver, was also important to effective jamming, but they applied a pass-fail whiteness test rather than measuring the whiteness quantitatively. If the display of a spectrum analyzer connected to the output of the IF filter of the victim receiver displayed a trace that was roughly the same shape as the transfer function of the IF filter, the noise was considered to be "white".

4.3.2 IF Noise Quality. As has been suggested by the previous theoretical work in this chapter, noise from an FM/N jammer will never be perfectly white, and, in the case of NBFM/N, may be significantly "colored". Furthermore, it seems that in some situations, there is a trade-off that can be made between whiteness and gaussianity. A noise source that is somewhat whiter than another source of the same gaussianity should theoretically be a better jammer for the same amount of power. These considerations caused Daly to introduce two new noise quality measures: IF noise quality and RF noise quality.

RF noise quality has been described qualitatively in Chapter 2 of this thesis, and it is suggested there that RF noise quality is not universally applicable as a noise quality measure. Therefore it will not be considered further here. IF noise quality, on the other hand, is similar to Turner noise quality, in that it measures the gaussianity of the signal at the output of the IF filter of the victim

receiver, and thus includes consideration of the parameters of receiver being jammed, as well as being independent of the particular method used to inject noise into the victim receiver. However, IF noise quality also makes a quantitative measurement of the whiteness of the output of the IF filter. How it does this warrants some attention.

IF noise quality is based on the product of two penalties, one associated with the flatness of the frequency domain: p_f and one associated with the gaussianity of the univariate pdf of the signal measured in the time domain: p_t. These numbers each have a maximum value of 1, thus the product has a maximum of 1, and specific values associated with particular FM/N signals may be multiplied by 100% in order to obtain a percentage noise quality.

The penalty p_t is calculated by in a manner somewhat similar to the first three error measures used in Turner noise quality, in that it is based on a histogram composed of equal width voltage bins. However, instead of making a direct comparison, it converts the histogram into a sequence of sample pdf estimates, and compares these estimates with the ideal gaussian pdf at corresponding points. Using the same notation which was introduced above, this could be written as:

$$p_t = \frac{1}{K}\sum_{i=1}^{K}\sqrt{\frac{(p_s[i]/N\delta v - p_G(v_{ci}))^2}{p_G^2(v_{ci})}} \tag{88}$$

where v_{ci} is the midpoint of the ith bin and $p_G(v_{ci})$ is the value of the Gaussian pdf at that point. Daly states that this penalty was chosen as the measure of gaussianity, based on an algorithm given by Shanmugan and Breipohl (23:497–500) and he finds the results that it gives consistent with the theory of FM/N and well correlated with the Turner noise quality (8).

The frequency domain penalty p_f is a little more problematic. The manner in which it is assessed is straightforward. It is calculated on the basis of a trace of the spectrum of the output of the IF filter, as displayed on a frequency analyser which has been set to cover the 3dB bandwidth of the IF filter. The power underneath the trace is then compared to the power underneath a constant theoretical trace having magnitude equal to the maximum magnitude of the actual trace.

The frequency-domain penalty is a great success in terms of simplicity, but it suffers from three drawbacks 1) it does not take into account the shape of the filter, 2) it is very heavily influenced by the processing which the spectrum analyzer can perform, and 3) it is subject to wild fluctuations because of a single spurious data point.

Daly was aware of all these problems, and he comments on them for several paragraphs:

> Note that this penalty is conservative because it is based on the erroneous assumption that the ideal trace can be uniform across the 3 dB bandwidth ... the 3 dB bandwidth of a filter is, by definition, non-uniform.

(8) He also notes that p_f should have increased as the WBFM/N bandwidth increased for a constant B_m; however, this did not take place because of "trace averaging provided by the video bandwidth selected on the HP 8566B spectrum analyzer ..." (8).

However, despite the drawbacks, the concept of IF noise quality as a whole has some compelling features. It does, to a degree, measure the flatness of the spectrum in a quantitative sense, as well as measuring the gaussianity of the univariate pdf; furthermore, the fact that it is a percentage of unity lends it to use in jamming versions of the radar range equation. Daly gives a brief example of how it could be incorporated into Barton's equation for jammer temperature (a measure of the increase in effective input temperature produced by a jammer) (2:139) (8: 6-11). Turner noise quality, on the other hand, is completely unsuited for this type of insertion.

4.3.3 FFT-IF Noise Quality. These factors led to the development of a modified IF noise quality which will be referred to here as ***FFT-IF noise quality*** because it makes use of an FFT algorithm to find the whiteness of the spectrum, instead of relying on a spectrum analyzer trace. As in IF noise quality, two penalties are assessed for deviations from gaussianity and whiteness, p_t and p_f. The penalty p_t is calculated by a simple transformation of Turner Noise Quality:

$$p_t = 1 - \frac{1}{\text{TNQ}}. \tag{89}$$

Thus p_t retains the strong measure of gaussianity that was developed and experimentally verified by the team at Stanford, but also has the property that increasing noise quality gives us a value increasingly close to one, making it suitable for insertion into a jammer power equation.

For extremely low values of noise quality, a Turner Noise Quality of less than 1 will give us a negative p_t, which has questionable meaning, but noise jammers very rarely produce noise that is that poor in practice (recall that a perfect sinusoid has a theoretical TNQ of 1.5). More reasonable values of TNQ for operational jammers range from 4 (giving us a $p_t = .75$) up to 10 or higher (giving us $p_t > .90$).

This method for calculating p_t does not produce significantly different results from the method Daly suggests for calculating p_t; however, it has the advantage of being easily computed if TNQ for a system is already known.

The method for calculating p_f is where the significant theoretical difference between ρ_{IF} and ρ_{FFT} is found. For ρ_{FFT}, p_f is calculated by using a digital oscilloscope to take correlated data samples (sampling at higher than the Nyquist rate), taking the FFT of the data samples to find an estimate of the spectrum of the noise process, and then dividing point-by-point by the discrete frequency transfer function of the IF filter.

Essentially, the problem that must be solved is *not* the determination of whether or not the process coming out of the filter is white; it is already known that it isn't. The real problem is to determine how closely the output of the filter conforms to the ideal output if the input to the filter were perfectly white. If the transfer function of the IF filter is again taken to be $H(f)$, then the Fourier transform of the post-filter samples may be taken to be $\hat{P}_{yy}(f)$, where $\hat{P}_{yy}(f)$ is an estimate of the spectrum $P_{yy}(f)$ obtained by passing some signal $x(t)$ through H and:

$$P_{yy}(f) = H^2(f) \cdot P_{xx}(f) \tag{90}$$

This implies that an estimate of the spectrum of the input signal, $\hat{P}_{xx}(f)$ may be found as:

$$\hat{P}_{xx}(f) = \frac{\hat{P}_{yy}(f)}{H^2(f)} \tag{91}$$

The question now is, how closely does $\hat{P}_{xx}(f)$ approximate a white spectrum of the same average power, denoted as $P_{ww}(f)$? At this point, the question is answered by finding the absolute point-by-point difference from the mean of $\hat{P}_{xx}(f)$ and dividing this by the number of points in the spectrum. This quantity is the average error power. The normalized error power is found by dividing the average error power by the average power in $\hat{P}_{xx}(f)$, and the frequency domain penalty is then the difference between this normalized error power and one. In other words, if there are N points in the spectral estimate $\hat{P}_{xx}(f)$, and the mean of $\hat{P}_{xx}(f)$ is μ_x, then:

$$p_f = 1 - \frac{\frac{1}{N} \cdot \sum_{i=1}^{N} |\hat{P}_{xx}(f_i) - \mu_x|}{\mu_x} \tag{92}$$

This retains the advantage of approaching unity as the estimate of the spectrum of the input to the IF filter becomes increasingly white, and it avoids the drawbacks associated with spurious data points, the specific shape of the filter being used, and processing performed under different settings on a spectrum analyzer.

The final value for the FFT-IF noise quality is denoted ρ_{FFT} and is found as before:

$$\rho_{FFT} = p_f \cdot p_t \tag{93}$$

and it can be used in jammer noise calculations or to modify linked budget calculations based on the jammer signal power needed just as has been suggested of ρ_{IF}.

4.4 Summary

In this chapter, ideal noise was found to be white in the frequency-domain and also to have a gaussian univariate probability density function. The theory of FM was used to develop the spectrum of the FM/N signal and to define four types of FM/N jamming: WBFM/WBN, WBFM/LFN, NBFM/WBN and NBFM/LFN. The characteristics of these four types of jamming in terms of spectrum of received signal and pdf of received signal were examined qualitatively, and it was concluded that WBFM/WBN was the only type of FM jamming which is good for masking jamming both spectrally and in terms of the gaussianity of its pdf. However, it was found that the pdf of the NBFM/LFN system may appear gaussian under certain pathological conditions. Thus it was concluded that merely looking at the pdf of a signal was insufficient to conclude that it was "good" noise. An expression was found for the minimum baseband bandwidth and RF bandwidth required for a WBFM/WBN system, based on the bandwidth of the victim receiver, and this was converted into a minimum sweep-to-victim ratio (SWR).

Lastly, three noise quality measures were discussed. Turner noise quality was presented and it was pointed out that Turner noise quality does not measure the spectrum of the noise quantitatively for whiteness. IF noise quality as defined by Daly was examined and found to be excellent in concept but lacking in implementation as regards the assessment of a penalty for spectral deviation from ideal flatness. A new noise quality measure was introduced which modifies IF noise quality in order to make it a more consistent and more accurate measure.

V. Experiments

This chapter discusses the experiments which were carried out to support the theory given in the preceding chapter, to demonstrate the concepts which were mentioned, and to both verify and suggest modifications to the noise quality measurement techniques proposed and implemented in the preceding thesis (8). The experiments are grouped by the experimental setup employed rather than by their function, and each experimental setup performed more than one function in terms of supporting theory, demonstrating concepts and responding to the suggestions of the previous work.

The first group of experiments used generally the same setup that was employed by Daly in 1992, the exceptions being some simple changes to computer programs and some changes in the bandwidths and peak frequency deviations chosen. The second group used an FM/LFN setup designed to demonstrate the behavior of NBFM/LFN as theoretically described in Chapter 4, and to demonstrate the specific failing of Turner noise quality and any other measure of noise quality which only considers the whiteness of the noise spectrum in a qualitative sense. It also featured the use of new computational hardware, and a new program written to demonstrate the new measure of noise quality which was introduced in Chapter 4. The program is written in Matlab and a listing is included following the C programs in Appendix A. (The new hardware and the C programs were used to increase the speed of acquiring and processing data from the oscilloscope in order to reduce the variance of the data samples.) The third group of experiments made measurements of a commercial FM/N radar jammer in order to demonstrate how the techniques of noise quality measurement developed in the initial laboratory setup could be extended to a more practical situation. This group of experiments used the C programs and the Matlab code exclusively.

5.1 Verification and Use of the Daly Simulation

In response to the conclusions and recommendations made by Daly (8:7), and in support of the theoretical results found in Chapter 4 of this thesis, roughly 200 noise quality measurements

were made, using what will be referred to in this chapter as the Daly Simulation. Details of the simulation are provided in Daly's work, but slight changes in parameters that Daly does not mention (such as the effect that the number of sample bins has on the chi-square calculation, or the gaps in sample histograms that result from specific voltage/division settings on the digital oscilloscope) require a short summarization of the equipment setup and some explanation of the computer programs used.

It should be noted that although a reasonable understanding of the basic techniques and concepts of the Daly Simulation can be easily conveyed here, an experimenter interested in reproducing the results found here should consult (8) for the full range of specific details. Equipment setup is explained thoroughly in Chapter 4 of that document, and listings of the HP Basic programs used are found in Appendix A of that document.

Along with the description of the Daly Simulation, a critique of some aspects of the simulation is offered. In general, the simulation was good. Specifically, it gave reasonable and correct readings of Turner noise quality, IF noise quality and RF noise quality for the noise sources being measured, when it was set up correctly. However, it was concluded in the course of the experimental work reported on here that two portions of the processing programs employed in the simulation need modification. Firstly, the original software of the Daly simulation sampled at greater than the Nyquist and then rejected a number of samples because they were correlated. The reason for this is explained here, and an alternative approach is offered. Secondly, the Daly simulation adds a chi-square test to the computation of Turner noise quality. Within the context of the Daly Simulation, there are some circumstances where the chi-square test provides a good measure of gaussianity, but as a general rule, it does not. In part, this has to do with quantization error introduced by the oscilloscope. Some of this will be addressed here, and some of it will be covered in more detail in Chapter 6 where results of the experiments in general are discussed, and an alternative approach to this is also suggested.

Table 1. Table of Equipment for Daly Simulation

ITEM	*COMPANY*	*MODEL*
Simulated Jammer		
Noise Generator	Hewlett Packard Co.	HP3722A
Signal Generator	Hewlett Packard Co.	HP8640B
Simulated Receiver		
Signal Generator	Hewlett Packard Co.	HP8640B
Dual Hi/Lo Filter	Waveteck Rockland	Model 852
Mixer	Anzac	MD 141
Measurement Equipment		
Oscilloscope	Hewlett Packard Co.	HP54111D
Spectrum Analyzer	Hewlett Packard Co.	HP8566B
Computer	IBM	286 PC
Coprocessor	Hewlett Packard Co.	HP82324A

5.1.1 Equipment. The Daly Simulation consists of three parts: 1) A simulated FM/N jammer composed of a white gaussian noise generator and an FM modulator, 2) A simulated receiver composed of a signal generator and mixer used to heterodyne the jammer signal down to an intermediate frequency and a bandpass IF filter, and 3) a noise quality measurement system composed of a programmable digital oscilloscope, a programmable digital frequency analyzer, and a personal computer. A block diagram of the equipment setup is shown in figure 6.

For reasons of practicality and manageability, all equipment was chosen to be commercially available and of a fairly generic nature, and it should be made quite clear that any similar system should produce reasonably similar results in terms of *general trends* in noise quality figures based on the conditions of NBFM/N and WBFM/N, and relationships between the bandwidth of the modulating noise and the bandwidth of the IF filter. However, because some of the observations made in verifying the Daly Simulation are peculiar to the specific equipment used and specific settings on that equipment, a table identifying the particular pieces of equipment is included in table 1.

The specific capabilities of each piece of equipment can be discovered in the appropriate manual or by contacting the company. The limitations which led Daly to pick the specific pieces

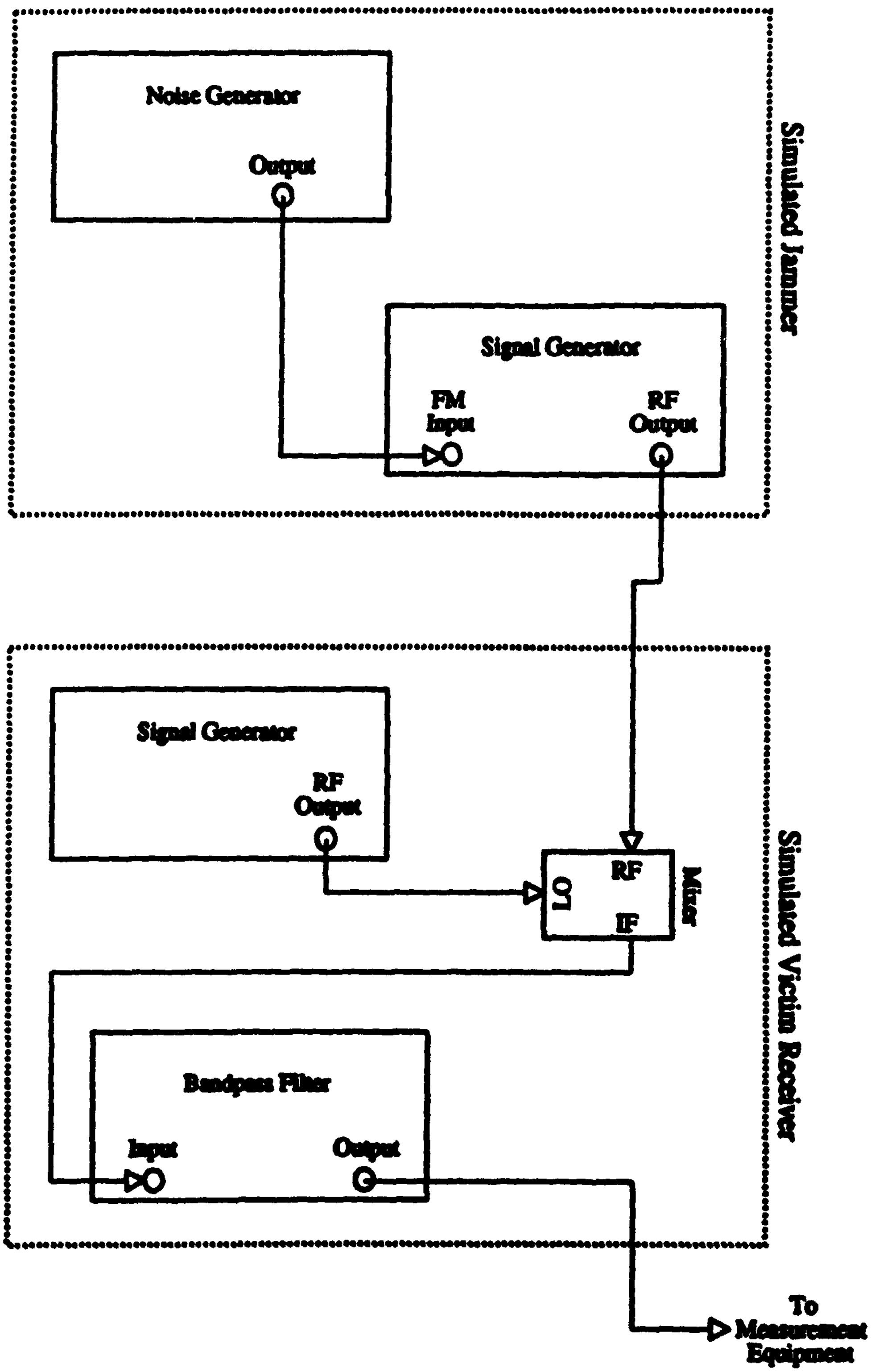


Figure 6. Block Diagram of Equipment setup

of equipment which he did, based on the choices he had, are described in his thesis (8:4-4). For the purposes of verifying the Daly simulation and measurement of noise quality, it was only necessary to insure that: 1) the equipment did not preclude the investigation of all four types of FM/N jamming, and 2) the oscilloscope and frequency analyzer were able to operate at the frequencies used by the FM signal and the output of the IF filter, and they produced sufficient data samples of sufficient quality for accurate processing.

The absolute values of of the three bandwidths which interact in an FM/N jamming scenario are, of course, important as factors in any system design, but for the purposes of investigating the phenomenon of FM/N and measuring noise quality, it is only the relative values of the three bandwidths which are important. In light of this then, we will describe the bandwidth limitations briefly.

The baseband noise produced by the HP3227A noise generator was bandlimited white gaussian noise with a Turner noise quality of about 10 when measured directly. The maximum bandwidth B_m which it could produce was 50 kHz. Successively narrower bandwidths could be produced with B_m of 15 kHz, 5 kHz, 1.5 kHz, .5 kHz, etc.

The peak frequency deviation, Δf_p, which determined the RF bandwidth, B_{FM}, was limited by the HP8640B signal generator to 1% of the lowest frequency in a tuning range. Thus the maximum B_{FM} could be, where B_{FM} is now an absolute rather than a 3dB bandwidth, was $2(.01)f_c$, and generally it was less. To insure wideband FM, the deviation ratio D was generally chosen to be at least 3. Thus Daly chooses $\Delta f_p = 3 \cdot 50$ kHz $= 150$ kHz, and this was a commonly used value during the verification of the simulation. This value implies an f_c then of at least 15 MHz. In actual practice a commonly used value was $f_c = 250$ MHz, so obtaining a sufficiently wide RF bandwidth to insure WBFM was not difficult.

The bandwidth of the IF filter of the victim receiver was a little more restrictive. The bandpass filter was composed of a lowpass filter with cutoff frequency f_{hi} followed by a highpass

Table 2. Exploratory FM/N scenarios

B_m	Δf_p	B_r
WBFM/WBN		
50 kHz	150 kHz	25 kHz
50 kHz	150 kHz	40 kHz
WBFM/LFN		
50 kHz	150 kHz	100 kHz
5 kHz	150 kHz	50 kHz
NBFM/WBN		
50 kHz	50 kHz	40 kHz
50 kHz	60 kHz	25 kHz
NBFM/LFN		
50 kHz	50 kHz	100 kHz
15 kHz	10 kHz	50 kHz

filter with cut-off frequency f_{lo}, giving a 3 dB bandwidth of $f_{hi} - f_{lo}$. The filters were configured with a maximally flat passband response and a roll-off of 24 db/decade. The minimum frequency available for f_{lo} was theoretically dc; however, in order to avoid frequency foldover, it was decided not to go any lower than 10 kHz. The maximum frequency available for f_{hi} was 111 kHz. So the maximum bandwidth available for B_r was roughly 100 kHz, and B_r could be chosen successively smaller in bandwidths down to almost zero. When Daly used the simulation, he chose $B_r = 25, 50$ kHz. In the use of the simulation presented here, bandwidths were explored from 10 to 100 kHz, in increments of 10 kHz.

It is easy to see that with these frequency ranges, all four types of FM/N jamming schemes could be explored. Assuming that f_c is kept constant at 250 MHz, then typical [1] WBFM/WBN, WBFM/LFN, NBFM/WBN and NBFM/LFN scenarios for the purposes of exploration using the Daly Simulation might be as given in table 2

The capabilities of the spectrum analyzer and oscilloscope far exceeded the requirements placed on them as far as bandwidth is concerned, but the memory capacities of each device had

[1] The term "typical" is used loosely. Each of the cases specifically mentioned here, along with a wide variety of other cases, was explored. Some cases are borderline; other cases were chosen because they were more extreme, and thus more clearly demonstrated the characteristics peculiar to their category. The important thing to note is that you can move from any one scenario to any other scenario by holding any single bandwidth constant and appropriately varying the other two.

the potential of imposing limitations. The oscilloscope was able to hold 8192 samples at a time per channel, but for the purposes of developing a histogram to estimate the pdf of the IF filter output, it was necessary for all the samples to be decorrelated, thus nothing was lost by capturing 8K of samples, downloading them for processing, obtaining a second 8K, downloading that, etc. Thus the practical number of samples available for processing is much greater than 8K when the samples were intended to be decorrelated, as is always the case in the Daly Simulation when the Turner, IF and RF noise qualities are calculated. If one channel is used to record the baseband noise and a second channel is used to record the noise in the victim receiver, records of both channels may be obtained for purposes of comparison.

The last characteristic of the oscilloscope which had some bearing on the measuring of noise quality was its amplitude resolution. The oscilloscope display had graticules seperating it into eight divisions in voltage amplitude. The maximum and minimum voltages recorded by the oscilloscope were set indirectly by specifying a number of volts per division (a typical value was 10 mV/division, giving a range of 80 mV total). This voltage range was divided by the oscilloscope into 254 quantization levels so that the amplitude of a sample falling within the ith voltage range, v_i where:

$$\frac{1}{254} i(v_{\max} - v_{\min}) < v_i < \frac{1}{254}(i+1)(v_{\max} - v_{\min}) \tag{94}$$

would be recorded as a one-byte integer with value between 0 and 255. (The values of 0 and 255 were reserved for recording "holes" and values that exceeded the range being considered. These digital values could be easily converted to their analog equivalents, and, in fact, this was done in the Daly Simulation to find the true mean and true variance of the signal, although this conversion has no theoretical effect on the calculation of the componenet of noise quality measures that focus on gaussianity. (A histogram does not become more or less gaussian by adding or scaling by a constant.)

The memory capacity of the spectrum analyzer had only an indirect bearing on the resolution of the data gathered for processing. The spectrum analyzer would only return 1000 data points at a time; however, by changing the video bandwidth, it was possible to get it to average a greater or smaller number of passes before producing a given set of 1000 points.

This somewhat tedious explanation of hardware details is given solely to explain two points which should be noted here: 1) The number of voltage bins which could be chosen for the purposes of forming a histogram was absolutely limited to 254, with the result that quantization error in the histogram could not be arbitrarily reduced, and 2) Choosing the minimum and maximum voltages carefully had an important impact on the calculation of noise quality. If the voltage range was too great, only a few voltage bins around the center of the histogram would be filled. If, on the other hand, the voltage range was too narrow, the tails of the histogram would be clipped. Both problems virtually guarantee a noise quality reading which is inaccurate. This resolution limit did not seriously hamper the measurement of noise quality, it merely necessitated that a certain amount of care be taken in the use of the hardware and software in order to obtain valid results.

5.1.2 Summary of experimental procedure for Daly Simulation. Three general types of measurements can be made using the equipment set-up described above and the HP BASIC programs written by Daly: 1) A time domain or frequency domain sample of the baseband or RF noise may be taken from the oscilloscope or spectrum analyzer and stored as a data file on the PC for further processing, or perhaps to generate a display 2) RF noise quality may be measured, or 3) Turner noise quality or IF noise quality may be measured. In order to carry out the first type of measurement, it was necessary to control the three bandwidths involved, and the amplitude of the IF signal.

The modulating noise bandwidth could be controlled by means of the switch on the noise generator. As noted before, it could be chosen from 50 kHz down to 5 Hz, at powers of 10 multiplied by either 5 or 15 Hz.

The RF bandwidth could be controlled by means of the peak frequency deviation knob on the HP signal generator configured as an FM modulator as follows. The peak frequency deviation control is set to a certain range (for example: 2.56 MHz). The meter on the SCALE panel then indicates the actual peak frequency deviation as a value less than or equal to the peak frequency deviation indicated by the position of the knob. (For example, if the position of the control is set to 2.56 MHz, then the light on the SCALE panel indicating "0-3" will light up, and a meter reading on the 0-3 scale of ".15" would indicate an actual peak frequency deviation of 150 kHz.) The actual peak frequency deviation may be fine-tuned to a particular value by using the fine-tuning control located in the center of the peak frequency deviation control. Additionally, the RF bandwidth could be controlled by changing the amplitude of the output of the noise generator. If the settings on the signal generator (aka FM modulator) were held constant, then the peak frequency deviation could be increased by increasing the rms voltage of the output of the noise generator.

The IF bandwidth was controlled solely by dual hi-lo filter which could be varied by as little as 1 Hz. For purposes of the verification of the Daly Simulation, the IF center frequency was always chosen to be at the center of the IF filter. In other words,

$$f_{IF} = \frac{1}{2}(f_{hi} - f_{lo})$$

It can easily be shown that the IF center frequency may be varied by holding the center frequency of the FM modulator constant at some f_c and varying the frequency of the signal generator in the simulated receiver as:

$$f_{receiver} = f_c + f_{IF}$$

or by holding the frequency of the signal generator in the simulated receiver constant at some f_c and varying the center frequency of the FM modulator as:

$$f_{\text{FM modulator}} = f_c + f_{IF}.$$

Either method is equivalent. In the experiments done in the context of this thesis, the signal generator producing the reference signal for the receiver was generally held constant at 250 MHz, and the center frequency of the FM modulator was varied as 250 MHz + f_{IF}.

The amplitude of the IF signal could be controlled by varying the rms voltage output of the noise generator, the output of the signal generator used as an FM modulator, and by the output of the signal generator used as a mixer in the simulated receiver. Varying any or all of these parameters has no effect on the noise quality of the output of the IF filter other than indirectly: if the rms value of the output of the IF filter is increased, then the voltage range of the oscilloscope must also be increased in order to meet the requirement that clipping of the signal not be too severe, as discussed above in section 5.1.1. Similar care must be taken if the rms value of the output of the IF filter is descreased.

Once the amplitude and the various bandwidths of the given setup are fixed, it is only necessary to ensure two things: 1) that the appropriate signal (i.e. baseband noise, RF signal, or IF output) is directed to the oscilloscope or spectrum analyzer that data is desired from, and 2) that the measuring device is connected by HP-IB bus to the HP coprocessor in the PC being used for signal processing and data storage. The settings of frequency span on the spectrum analyzer and sampling rate on the oscilloscope should be set to whatever values seem appropriate to capture the essential elements of information. It is suggested that if the time-domain data is to be used to plot a sample noise waveform, then the sampling rate should be at least twice the maximum frequency of the noise waveform; preferably several times the maximum frequency. If, however,

the time-domain data is to be used to form a histogram, it is necessary that the noise data be uncorrelated so "slow" sampling is mandatory.

When these considerations are met, then the appropriate program may be run (either TIMEDMN.BAS or FREQDMN.BAS when using a PC with the HP coprocessor.) Details on the use of the programs and program listings are found in (8:4), although one is advised to beware of minor errors.

In order to make either of the other three measurements (RF noise quality or IF or Turner noise quality), it is important to pay attention to all the suggestions made so far about bandwidths and amplitudes, and, in addition, for IF noise quality, *both* the oscilloscope and the frequency analyzer must be connected to the HP coprocessor in the PC via HP-IB cables, and care must be taken that the output of the IF filter be connected to the input of the spectrum analyzer and channel 2 of the oscilloscope. For the measurement of Turner noise quality, only the oscilloscope need be connected to the HP coprocessor in the PC, but care must still be taken that channel 2 is used to display the output of the IF filter. The function of channels 1 and 2 of the oscilloscope may be changed merely by making a few appropriate changes to the software; however, it seemed reasonable to reserve channel 1 of the oscilloscope for displaying the baseband modulating noise.

When measuring IF noise quality, the frequency span of the spectrum analyzer should be set to the theoretical 3dB bandwidth of the IF filter. When measuring RF noise quality, the frequency span of the spectrum analyzer should be set to cover the frequencies from $f_c - \Delta f_p$ to $f_c + \Delta f_p$. Furthermore, when measuring IF noise quality or Turner noise quality, the sampling rate of the oscilloscope must be "slow", in order to ensure that the data samples be uncorrelated. When these considerations are taken into account, then the appropriate program (IFNQ.BAS, RFNQ.BAS or NEWTURN.BAS, when using a PC with an HP coprocessor) may be run.

At this point some comments are in order concerning what is a sufficiently slow sampling rate to ensure uncorrelated samples. When the team at Stanford computed Turner noise quality, they sampled all their waveforms at a rate of 25 kHz, and this was always sufficiently slow. However,

because the filter bandwidths and IF frequencies used in the Daly simulation are so relatively low, more care must be taken.

The software solution implemented by Daly was to suggest to the user that sampling should take place at somewhere above twice the highest frequency present in the signal. For example, if the IF filter was set to a 40 kHz bandwidth extending from 60 kHz to 100 kHz, then sampling should take place at greater than 200 kilosamples per second. Because the oscilloscope will only sample at pre-defined rates, we must be content then with a rate of 250 kS/s. Daly's original programs then calculate the time constant of the IF filter as the reciprocal of the bandwidth, and all correlated samples are rejected. Thus, for example, when he chooses a 25 kHz bandwidth for his IF filter, he samples at a rate of 500 kS/s, collects 8192 samples, and rejects all but every 11th sample, leaving him with 781 uncorrelated samples. (see Table C-1, in appendix C of (8)). His explanation of this, given in Chapter 6 of (8) is incorrect and will not be repeated here. Essentially, the reason for sampling at the higher rate is so that the display on the oscilloscope bears some resemblence to the noise waveform being sampled.

If, however, one is only concerned with the univariate probability density of the noise (i.e. with forming a valid histogram) more data can be gathered more efficiently by merely choosing a sampling rate slower than the reciprocal of the IF bandwidth, and then keeping all of the samples. Thus, for example, it is suggested here that if a receiver bandwidth of 30 kHz is chosen, one should sample at the next slower sampling rate possible under the constraints of the oscilloscope, which in this case is 25 kS/s. If a receiver bandwidth of 25 kHz is chosen, then the appropriate sampling rate would be 10 kS/s. In all cases, all samples taken should be kept. The software changes necessary to accomplish this minor modification of the Daly simulation are discussed in Chapter 6 in the context of results from the verification experiments.

The most developed piece of software in the Daly Simulation was the program NEWTURN.BAS. In addition to merely calculating the Turner noise quality, it also produced a graphical respresenta-

Table 3. Variations of Parameters in Daly Simulation

	software
1)	the number of data samples taken
2)	rejection of a number of data samples
	oscilloscope
3)	the voltage ranges on the oscilloscope
4)	the sampling rate of the oscilloscope
	bandwidths
5)	the peak frequency deviation of the FM modulator
6)	the IF bandwidth of the filter
7)	the noise bandwidth
	amplitude changes
8)	the rms output of the noise generator
9)	the amplitude of the local oscillator

tion of the histogram and calculated the theoretical and actual chi-squared values associated with a normal pdf of the same variance as the noise samples and with the the histogram. These values were denoted as χ^2 and X^2, respectively, and they were used to apply the chi-square normality test. In all the noise quality measurements which were made, these two values were noted.

5.1.3 Experiments Using the Daly Simulation. The first set of experiments which were done using the Daly Simulation (or slight modifications of the simulation) were primarily for the purposes of verifying it and looked for: 1) changes in the noise quality measures consistent with the theoretical understanding of the various FM/N scenarious, and 2) changes in the noise quality measures due to abnormalities in the measurement that might arise from poor parameter choices in the setup. In other words, two questions were asked: "Do the noise qualities as measured by the Daly Simulation techniques actually increase and decrease when the FM/N scenario changes cause theoretical increases and decreases in noise quality?" and "Under what conditions is the noise quality figure given by the Daly Simulation likely to be invalid?" The parameters which were varied are as shown in table 3.

The software was successively modified so that the shortest number of data samples taken was 1490, while the maximum taken was 24576. In addition, software changes were made so that

some data was deliberately correlated to see how the histogram would be affected, while most data was uncorrelated.

The voltage ranges on the oscilloscope were generally kept at 80 mV, since it was found that this worked well with an amplitude setting generated by selecting a 1 Vrms output from the noise generator, a 0 dBm setting on the output of the FM modulator, and a 0 dBm setting on the output of the signal generator in the simulated receiver. However, under certain circumstances, the voltage range was increased to as much as 640 mV, and decreased to as little as 8 mV (the absolute lower limit of the oscilloscope).

The baseband noise bandwidth was kept at 50 kHz for most of the experiments but was lowered to as little as .15 kHz. The peak frequency deviation indicated by the FM modulator was most often kept at 150 kHz, but was lowered to as little as 50 kHz, and increased to as much as 300 kHz. The IF bandwidth was kept within the range of 10 to 100 kHz. Experiments which were performed to demonstrate the application of the Central Limit Theorem (CLT) were generally performed by holding other parameters constant and decreasing the IF bandwidth.

The rms output of the noise generator was most often kept at 1 Vrms, but was increased to both 3 and 3.6 Vrms in order to generate a larger peak frequency deviation in some scenarios. The output of the receiver signal generator was most often kept at 0 dBm, but was increased to 10 dBm on a number of occasions in order to amplify the signal entering the IF filter.

For any given setting of the equipment, at least three calculations of noise quality were made; sometimes as many as 20 calculations were made while holding specific parameters constant.

After the Daly Simulation was verified, it was used to demonstrate the Central Limit Theorem effect of FM/N and also to illustrate some of the characteristics of each of the types of FM/N mentioned in this thesis.

The actual raw data, in terms of Turner noise quality, IF noise quality, χ^2 and X^2 which were obtained from all the experiments are tabulated in Appendix B. Each table of data is prefaced by

a listing of the particular parameter settings which produced it. A graphical presentation of the data is given in Chapter 6, along with some explanations of how the data either supported or failed to support theoretical predictions.

5.2 The Pathology of NBFM/LFN

The experiment described in this section was designed to demonstrate the problem with any noise quality measure that relies solely on a measurement of the probability density of the noise in a quantitative sense. Specifically, it demonstrates how noise generated by a NBFM/LFN setup can suffer from both of the two problems which plague FM/N systems and yet still have an acceptable Turner noise quality (i.e. a TNQ of greater than 4).

In general, a WBFM/LFN system will receive a low noise quality rating based on gaussianity because, although the noise which is produced when the RF signal sweeps through the passband of the receiver is gaussian, there will generally be some "dead time" between one sweep and the next. This dead time will produce an output of the IF receiver of zero, and thus the true pdf of the noise produced by the WBFM/LFN system will have a delta function at zero, and a histogram of data samples of the WBFM/LFN will have a sharp peak in the center which will generally cause the Turner noise quality to be quite low: on the order of less than 4.

Such a system was generated by choosing $B_m = 15$ kHz, $\Delta f_p = 300$ kHz, and $B_{IF} = 50$ kHz. It was then demonstrated that by lowering the peak frequency deviation, (thus deviating from WBFM/LFN toward NBFM/LFN) an increase in Turner noise quality could be produced, and, indeed, histograms of the noise samples also began to look more gaussian.

As noted above, the equipment used in this experiment was identical to that used in the first set of experiments with the exception that the processor controlling the digital oscilloscope was a 33 MHz 486 with a AT-GPIB NI-488 board installed in it. A C program was used to obtain data from the oscilloscope, and then processing on that data was done with the matlab programs found in

Appendix A. Raw data for this experiment is given in Appendix B, and a graphical representation of the data is given in Chapter 6.

5.3 Measurements on an Operational Jammer

The last set of experiments was done to demonstrate two things: 1) that noise quality measurements on an actual radar jammer could be made using essentially the same techniques developed while working with the Daly Simulation, and 2) that the algorithms developed using HP BASIC and the HP coprocessor could be translated to another programming language and implemented on different hardware with little difficulty.

A list of the hardware is found in table 4. Essentially it was composed of three parts: 1) the jammer breadboard (in three boxes) and the VT100 used to program it, 2) the simulated receiver which was composed of two signal generators, two mixers and two bandpass filters, one variable to certain discrete frequencies, and one fixed, and 3) the measurement and processing equipment, consisting of the same oscilloscope used in the first two sets of experiments and the PC and programs used in the second set of experiments.

The ECM Techniques Generator is a breadboard of the actual circuitry used in an operational jammer. The breadboard unit which provided the two mixers and the two IF filters was the same unit originally used by the research team at Stanford. The first IF filter had a center frequency of 750 MHz and a bandwidth of 15 MHz. The second IF filter had a center frequency of either 60 MHz or 20 MHz depending on which of a number of bandwidths were chosen. The bandwidths varied from 6.7 MHz down to .1 MHz. A 30 MHz barrage was generated at 6.22 GHz. This was then mixed down to the appropriate IF frequency, filtered, and noise measurements were taken.

There were no startling theoretical results (although the variation in noise quality present in a commercial jammer was surprising), but the two main goals which this experiment set out to acheive were generally acheived. Raw data from this experiment is shown in a table in Appendix B.

Table 4. Table of Equipment Used to Measure Noise Quality of Operational Jammer

ITEM	*COMPANY*	*MODEL*
Commercial Jammer		
ECM Techniques Generator		breadboard
Jammer Controller	Digital Equipment Corp	VT100
Simulated Receiver		
Signal Generator	Hewlett Packard Co.	HP618C +
Signal Generator	Hewlett Packard Co.	HP612A
Mixer 1	Stanford Reasearch Inst	breadboard
Mixer 2	Stanford Reasearch Inst	breadboard
15 MHz IF filter	Stanford Reasearch Inst	breadboard
variable filter	Stanford Research Inst	bradboard
attenuator	Hewlett Packard Co.	HP 8495B
Measurement Equipment		
Oscilloscope	Hewlett Packard Co.	HP54111D
Spectrum Analyzer	Hewlett Packard Co.	HP8566B
Computer	Compuadd	486 33MHz
Communications Board		GPIB NI-488

VI. Results

This chapter details the results of the experiments described in Chapter 5. The first section deals with the results of the measurements made to verify the Daly Simulation. Most of the attention is given to demonstrating the conditions under which the Daly Simulation produces results consistent with the theory of FM/N as outlined in Chapter 4, including the increase in gaussianity that occurs when B_{IF} is narrowed and other parameters are held constant. The behavior of each of the four types of FM/N as outlined in this thesis is demonstrated with graphs showing time domain waveforms of baseband and IF noise, IF spectra, and IF pdfs. Abnormal readings that result from poorly chosen parameters are mentioned briefly. Problems with applying the Chi-square test (which was implemented in the NEWTURN.BAS program) are explained, and an alternative is suggested. The results of making a few minor changes to the original Daly software are discussed.

The second section briefly describes the results of the experiment designed to demonstrate the weakness of pdf-only based measures of noise quality to accurately determine the usefulness of a NBFM/LFN jamming scenario. Particularly, it presents graphical results showing the increase in TNQ with the decrease in peak frequency deviation from a WBFM/N toward an NBFM/B scenario.

The last section presents data gathered from the measurements of an operational jammer. This data is not terribly interesting for its support of any theory about FM/N, since parameters such as the bandwidth of the modulating noise source or the peak frequency deviation of the FM modulator were not under our direct control. However, it does demonstrate that the techniques developed in the Daly Simulation can be transported to an operational environment with little difficulty.

6.1 Measurements Using the Daly Simulation

Not all of the variations in parameters which were explored in the verification of the Daly Simulation were able to demonstrate anything useful. Some of them demonstrated things which were trivial or already well-known from other fields, such as the fact that when the parameters of a random process are held constant and the number of samples of the random process is increased, there will be a corresponding decrease in the variance of the samples. These variations will be covered first, briefly, and an explanation of their effects on noise quality will be given.

The number of data samples taken is probably the most obvious parameter which affected the measurement of noise quality but had only an indirect bearing on the theory of FM/N. The original Daly program which computed Turner Noise Quality consistently took either 8192 or 16384 data samples at a sample rate of 500 KS/s, and then eliminated most of them because they were correlated. Unfortuanetly, the version of the program listed in Daly's thesis contains an error which causes it to keep consecutive samples which are still correlated. When this error was first discovered, there was some concern as to how great of an effect it had had on the measurement of noise quality. Additionally, there were questions about what would happen if the error was removed and the number of samples discarded was changed, and also, if the error were removed and the sampling rate of the oscilloscope lowered so that all samples were decorrelated.

The answers to these questions were:

1) When the error was present and a small number of samples were taken (that is a large number were discarded) the noise quality tended to be better than otherwise. This may have been due to the fact that they were still correlated, but possibly also had to do with an effect dealing with the number of samples which is explained in the next answer.

2) When the error was removed (so that all samples were truly decorrelated) the only effect of changing the number of samples was to increase the variance of the samples. A smaller number of samples produced a larger variance. The larger variance resulted in a smaller number of bins

being chosen (remember, Daly chose bin widths of $.2 \cdot \sigma$), and the larger number of bins produced a sort of smoothing effect that sometimes resulted in an increase in Turner Noise Quality of 1 or 2 points because it reduced the effect of quantization error. This result is fairly trivial, at least in terms of its reflection on the data Daly presented, because under normal circumstances the noise quality of the modulating noise will vary by that much or more over a period of half an hour.

3) When the part of the program which contained the error was eliminated completely, and the sampling rate was lowered so that all samples were decorrelated, there was no substantial change over the situation where correlated samples were taken and a certain number rejected, so long as the number of samples was kept constant. This was as expected.

In order to remove the bug from NEWTURN.BAS, simply change lines 1020 and 1030 to read:

```
1020   Anoise(Counter) = Anoise(N)
1030   Asorted(Counter) = Asorted(N)
```

In order to eliminate that part of the program and merely sample at a slower rate, delete lines 1000 to 1060 and line 900.

This covers the results of variations number 1,2, and 4 in table 3. The other result which was really trivial had to do with controlling the amplitude of the signal coming into the oscilloscope from the IF filter. It was found again, as expected, that if the rms amplitude of the noise generator was increased, this would increase the peak frequency deviation and increase the amplitude of the signal coming out of the IF filter. Similarly, if the local oscillator signal was increased, the IF filter output amplitude would increase.

6.1.1 Narrowing B_{IF} to Illustrate the CLT. The general increase in Turner Noise Quality which occurs when B_{IF} is narrowed under the condition of WBFM while the peak frequency deviation and the bandwidth of the modulating noise are held constant, can also be observed to

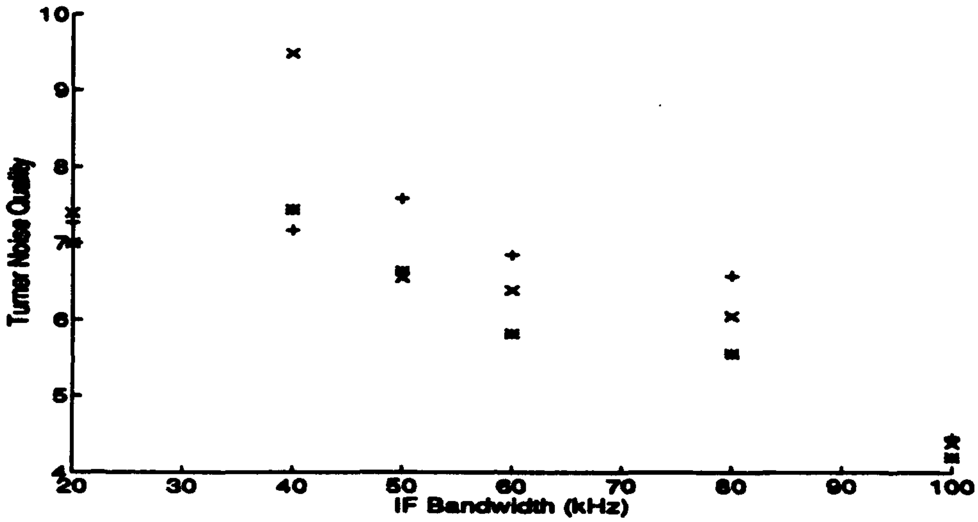


Figure 7. Central Limit Theorem Illustrated (TNQ vs B_{IF})

occur when B_m is increased under the condition of WBFM while the peak frequency deviation and B_{IF} are held constant. The decision to illustrate the CLT by narrowing B_{IF} was made merely because the bandwidth of the simulated victim receiver could be finely varied.

For this experiment, B_m was held constant at 50 kHz, and Δf_p was held constant at 150 kHz. B_{IF} was then narrowed from 100 kHz down to 20 kHz by steps of 20 kHz at a time. At each step, several computations of TNQ were made with different numbers of samples and different sampling frequencies. In each case, at least three measurements of TNQ were made at each bandwidth on the basis of 8192 data points at the highest sampling rate that still insured decorrelation of data points. A plot of the actual data points is shown in figure 20, and a graph of their averages is shown in figure 21. In each plot, TNQ is shown on the y-axis, and B_{IF} is shown on the x-axis.

As can be easily seen, there is an increase in TNQ with the narrowing of the bandwidth up to the point where the bandwidth of the IF filter is on the order of the modulating noise.

6.1.2 The Four Cases of FM/N Illustrated. Before showing the properties of each of the cases of FM/N, four figures are presented with the expectation that they will serve as a reference for

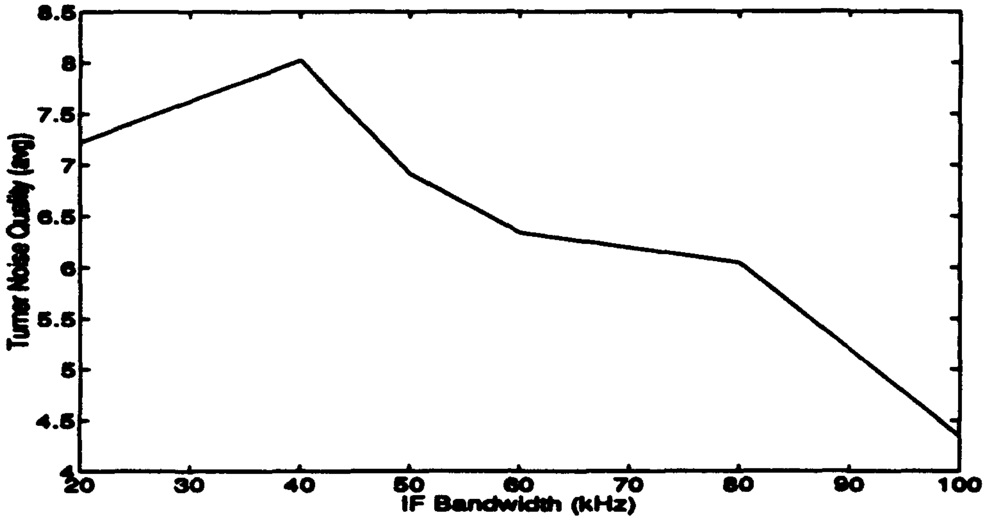


Figure 8. Central Limit Theorem Illustrated (TNQ vs B_{IF}) Averages

the corresponding figures under each FM/N category which are taken at the output of the victim receiver. Figure 9, shows the time domain sampled baseband noise, while Figure 10 shows the time domain sampled FM/WBN signal at RF. Note the relatively constant amplitude of the RF signal. [1] It is this feature of FM/N which makes it an efficient user of a TWT or other microwave amplifier.

Figure 11 shows the histogram of the FM/WBN signal while Figure 13 shows its spectrum at RF. Note the saddle shape characteristic of the pdf of a sinusoid. Also note the gaussian shape of the spectrum as predicted by Woodward's Theorem. Recall that the shape of the spectrum at the output of the IF filter will be a bandlimited copy of the RF spectrum.

The sampling rate of the oscilloscope for the baseband noise was 2.5 MS/s. The sampling rate for the RF FM/N signal was 1 GS/s. The span of the frequency analyzer was set to 1 MHz, the video bandwidth was 100 Hz, and the resolution bandwidth was 30 kHz.

[1] Unfortunately, we had reached the sampling limit of the oscilloscope, so this plot is not as clear as it should be.

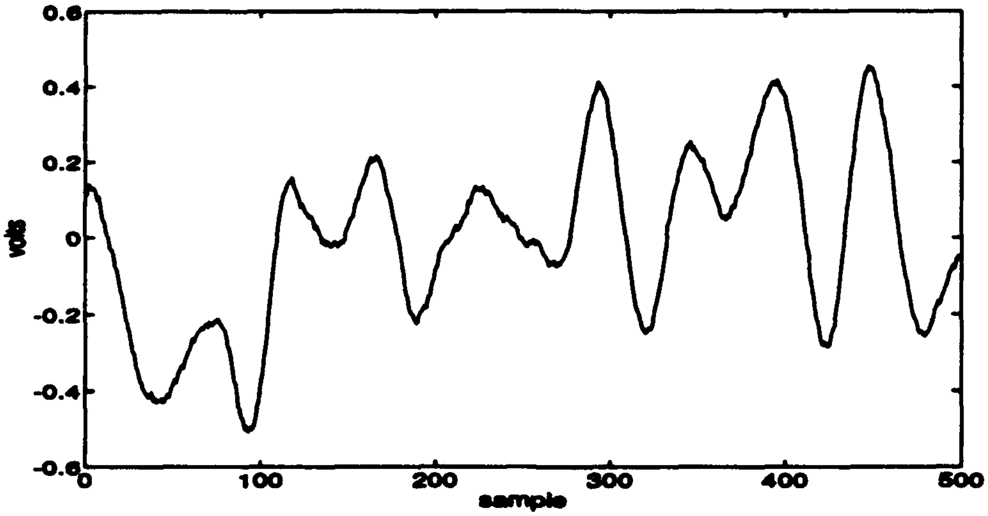


Figure 9. Time Samples of Baseband Noise

Lastly, Figure 12 shows the histogram of one million samples of the baseband noise. Note that it has a roughly gaussian shape. There are evidences of some quantization error, but clearly it would not be an ideal gaussian even if there were no quantization error. The TNQ for the baseband noise generally varied from 6.5 to 8.0 in the course of the experiments. The TNQ of the samples shown here is 7.0776.

The plots illustrating each type of FM/N are included in the sections following, with each section containing four plots corresponding to the first four plots describes above. The first two plots will show time domain samples of the baseband noise and the noise at the output of the IF filter of the victim receiver taken simulatneously at the same rate in order to show the relationship between the two signals if there is an obvious one. The third plot will show the histogram of one million time-domain samples of the output of the victim receiver, and the fourth plot will show the spectrum of the response of the IF filter of the victim receiver. The histogram of the baseband noise was found to be relatively constant irrespective of the baseband bandwidth which was chosen, therefore it would be redundant to include a histogram of the baseband noise in each section.

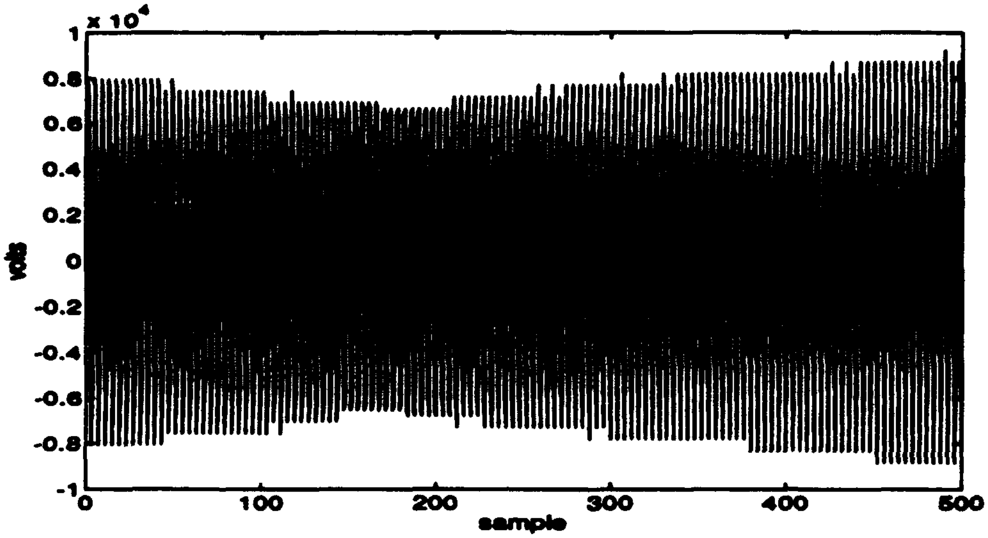


Figure 10. FM/WBN Time Samples at RF

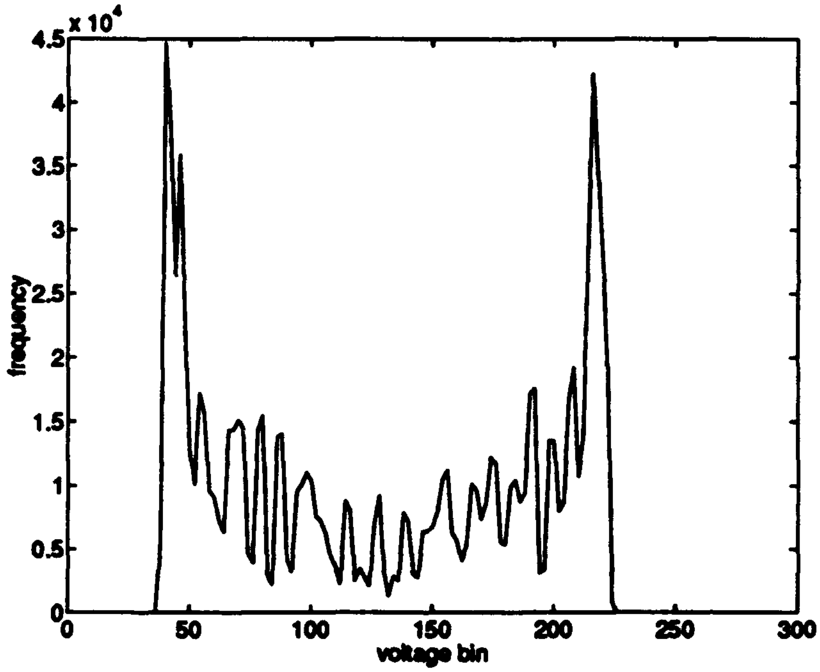


Figure 11. FM/WBN Histogram at RF

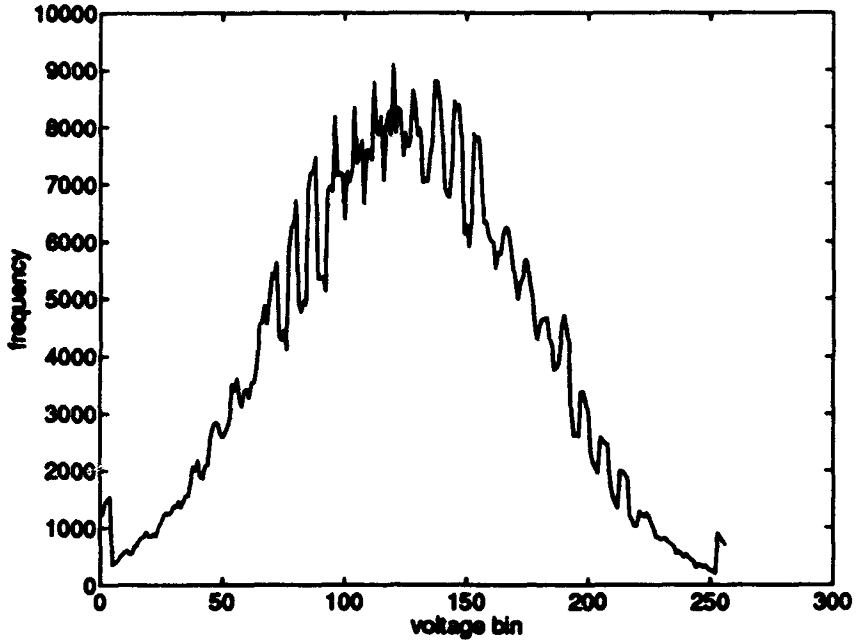


Figure 12. Histogram of Samples of Baseband Noise

The specific bandwidths chosen to illustrate the four cases of FM/N were arrived at by trial and error. In the case of WBFM/LFN, the bandwidth of the modulating noise was chosen to be relatively small in order to insure the presence of obvious "dead spaces" which are characteristic of WBFM/LFN. In the case of NBFM/WBN, a much more extreme case could easily have been chosen (it is not hard to lower the peak frequency deviation sufficiently to produce what is essentially a sinusoid at IF) but care was taken to merely produce a small amount of "wide-shoulderedness". The bandwiths for each scenario presented here are tabulated at the beginning of each section.

The plots of time-domain waveforms are produced with time along the x-axis, and voltage along the y-axis. The plots of histograms are produced with voltage bin number along the x-axis, and number of samples falling in each voltage bin along the y-axis. The plots of spectra are produced with frequency in kHz along the x-axis, and magnitude along the y-axis. In each case, the video bandwidth was chosen to be 100 Hz, and the resolution bandwidth was chosen to be 3kHz.

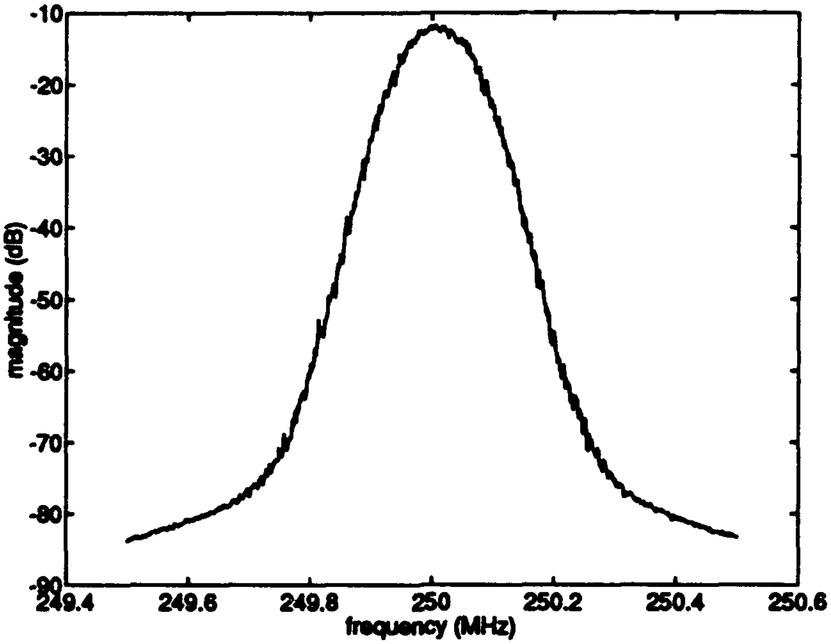


Figure 13. FM/WBN Spectrum at RF

6.1.2.1 WBFM/WBN. The frequencies used to demonstrate the characteristic behavior of WBFM/WBN are shown below.

B_m	Δf_p	B_{IF}
50 kHz	150 kHz	25 kHz

A sample waveform of the baseband noise is shown in Figure 14 while the signal which it generated at the output of the victim receiver is shown in Figure 15. Note that there is a constant response in the output of the victim receiver.

The histogram of 1 Meg of samples taken with the oscilloscope is shown in Figure 16, while the spectrum at the output of the IF filter is shown in Figure 17. Note that the histogram is roughly gaussian, as we would hope. Note also that the spectrum seems to generally follow the shape of the IF filter (as described in Chapter 5), indicating that the response of the filter is roughly equivalent

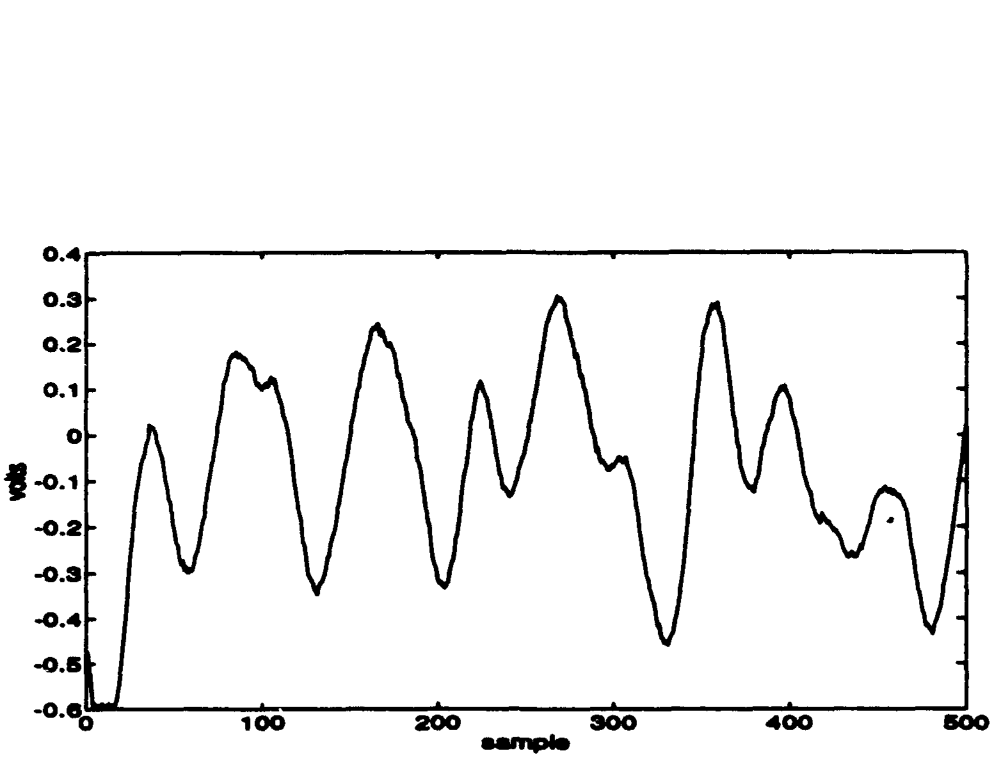


Figure 14. WBFM/WBN Baseband Noise (time samples)

to its response to white noise. The sampling rate chosen to generate the histogram was 25 kS/s, while the sampling rate chosen to generate the sample waveforms was 2.5 MS/s.

6.1.2.2 WBFM/LFN. The frequencies used to demonstrate the characteristic behavior of WBFM/LFN are shown below.

B_m	Δf_p	B_{IF}
5 kHz	150 kHz	50 kHz

A sample waveform of the baseband noise is shown in Figure 18 while the signal which it generated at the output of the victim receiver is shown in Figure 19. Note the dead spaces in the output of the victim receiver. Also note that each response or "ring" of the victim receiver begins when the baseband noise sweeps into the passband of the filter and has a duration which is based on the duration of the baseband noise in the passband or the time constant of the IF filter (i.e. $1/B_{IF}$) whichever is longer.

The histogram of one million samples taken with the oscilloscope is shown in Figure 20, while the spectrum at the output of the IF filter is shown in Figure 21. Note the sharp peak in the

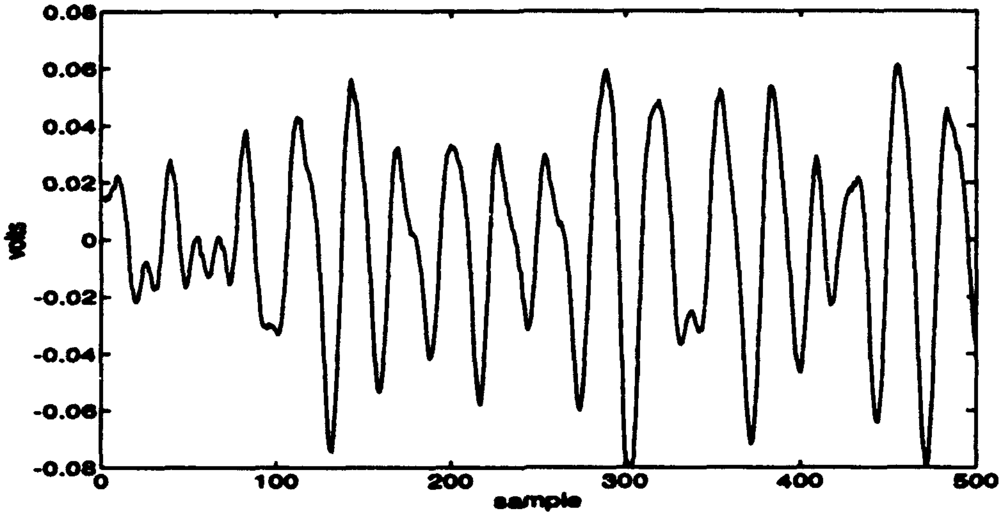


Figure 15. WBFM/WBN Output of IF Filter (time samples)

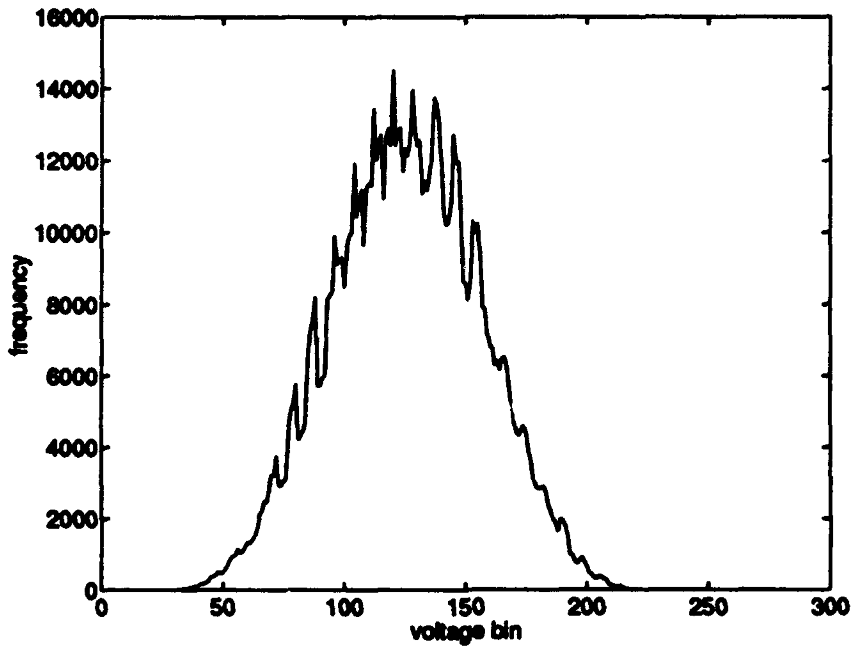


Figure 16. WBFM/WBN Histogram of Samples at Output of IF filter

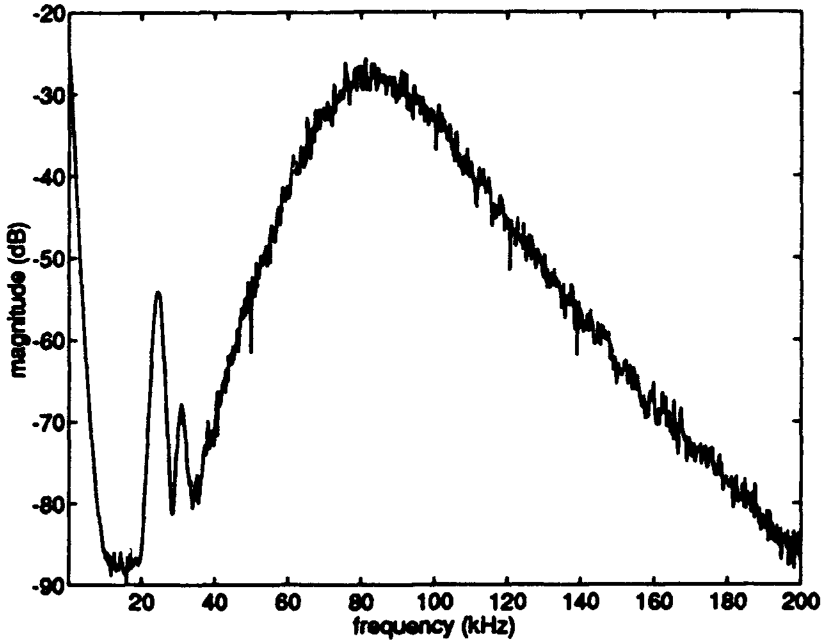


Figure 17. WBFM/WBN Spectrum of Output of IF Filter

histogram resulting from the dead spaces. The response of the filter is still roughly bandlimited white, but note the increase in frequency domain impulsiveness resulting from the fact that frequencies are being visited less frequently by the FM signal. The sampling rate chosen to generate the histogram was 50 kS/s, while the sampling rate chosen to generate the sample waveforms was 1 MS/s.

6.1.2.3 NBFM/WBN. The frequencies used to demonstrate the characteristic behavior of NBFM/WBN are shown below.

B_m	Δf_p	B_{IF}
50 kHz	60 kHz	25 kHz

A sample waveform of the baseband noise is shown in Figure 22 while the signal which it generated at the output of the victim receiver is shown in Figure 23. Note that the output of the

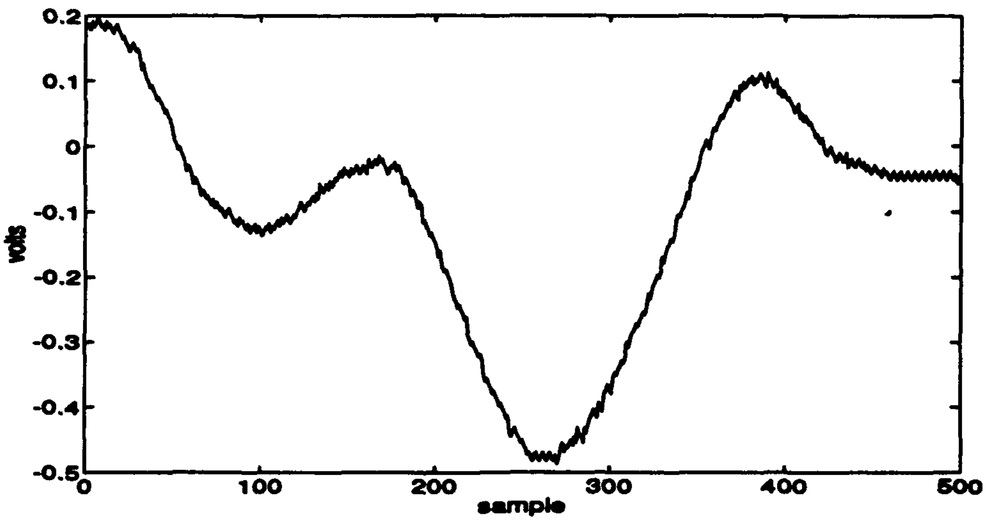


Figure 18. WBFM/LFN Baseband Noise (time samples)

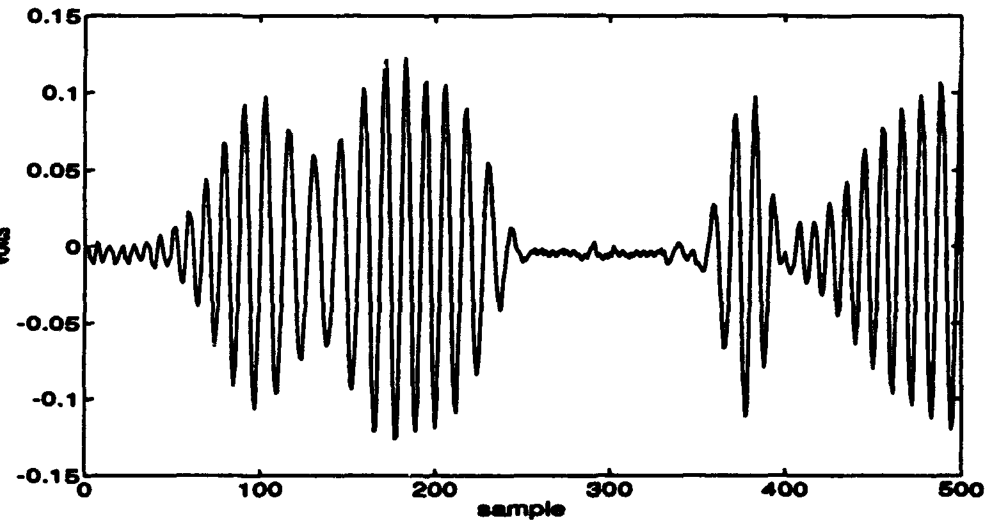


Figure 19. WBFM/LFN Output of IF Filter (time samples)

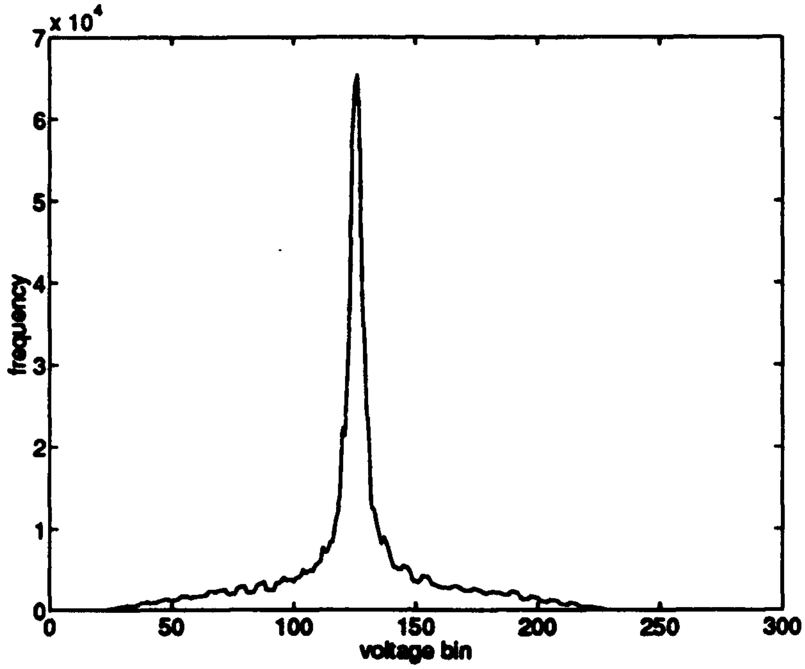


Figure 20. WBFM/LFN Histogram of Time Samples

IF filter now looks more like an AM/N output, in that the frequency of the output does not seem to vary much, but the envelope looks noisy.

The histogram of one million samples taken with the oscilloscope is shown in Figure 24, while the spectrum at the output of the IF filter is shown in Figure 25. The histogram shows clearly the tendency of NBFM/N toward "wideshoulderedness". The response of the filter to NBFM/WBN is now smoother in the frequency-domain than it was when the input was WBFM/LFN; however, note that it has a triangular shape in the filter's passband, indicating that the first convolutional term of the Middleton expansion is dominating. The sampling rate chosen to generate the histogram was 25 kS/s, while the sampling rate chosen to generate the sample waveforms was 1 MS/s.

6.1.3 NBFM/LFN. The frequencies used to demonstrate the characteristic behavior of NBFM/LFN are shown below.

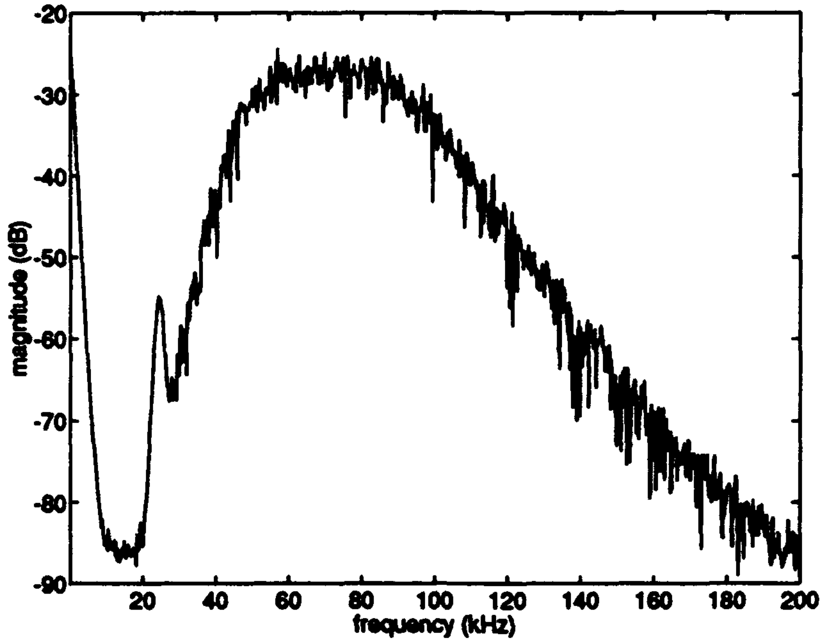


Figure 21. WBFM/LFN Spectrum of Output of IF Filter

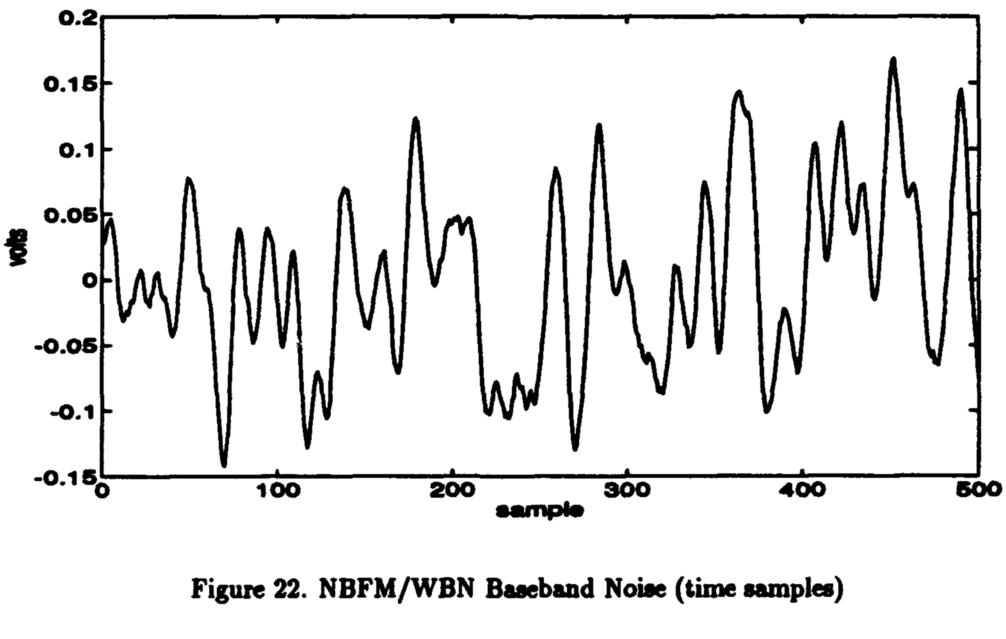


Figure 22. NBFM/WBN Baseband Noise (time samples)

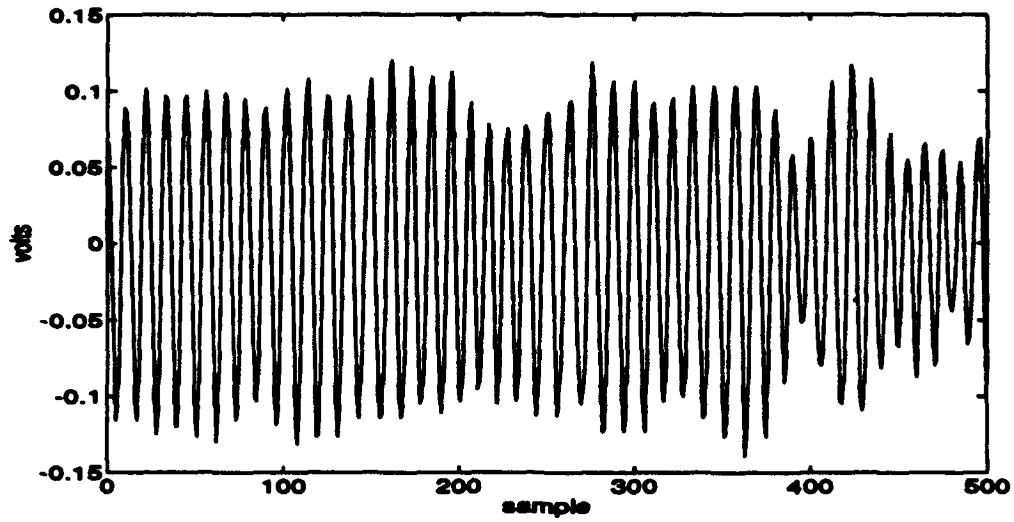


Figure 23. NBFM/WBN Output of IF Filter (time samples)

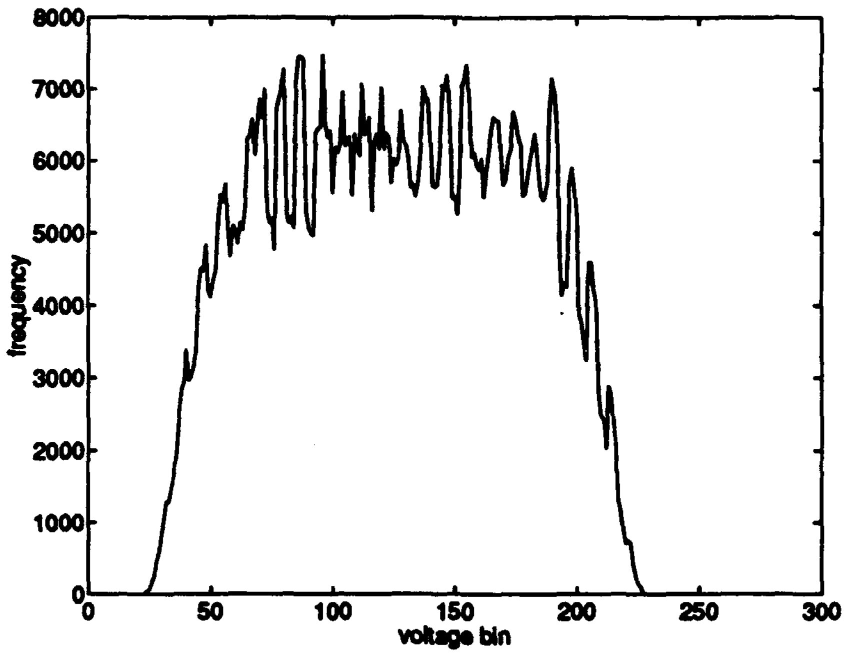


Figure 24. NBFM/WBN Histogram of Time Samples

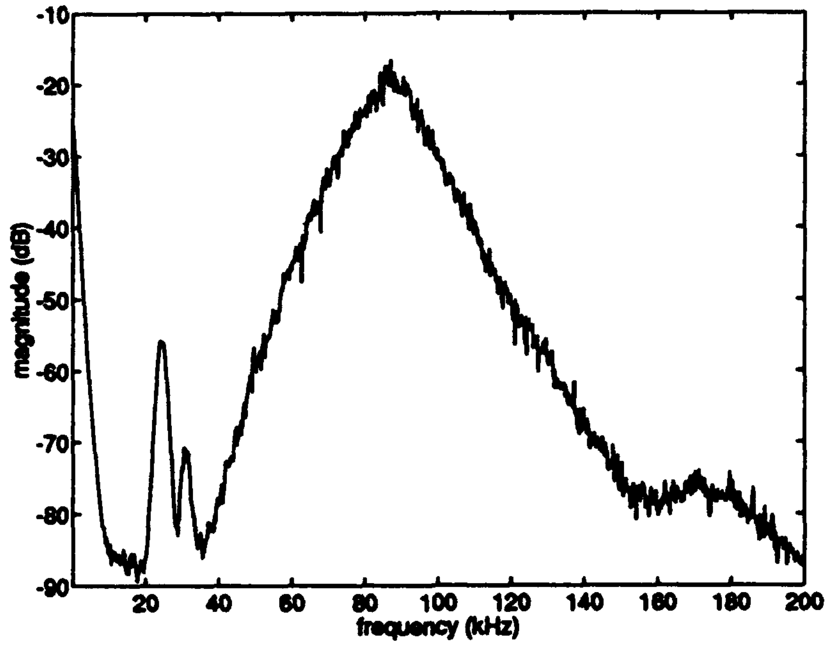


Figure 25. NBFM/WBN Spectrum of Output of IF Filter

B_m	Δf_p	B_{IF}
15 kHz	10 kHz	50 kHz

A sample waveform of the baseband noise is shown in Figure 26 while the signal which it generated at the output of the victim receiver is shown in Figure 27. Note that the output of the IF filter now looks even more like an AM/N output than did the NBFM/WBN case, in that the frequency does not change much at all.

The histogram of one million samples taken with the oscilloscope is shown in Figure 28, while the spectrum at the output of the IF filter is shown in Figure 29. It is now obvious from looking at the histogram that the output of the IF filter is mainly sinusoidal, since the histogram has the saddle shape characteristic of a sinusoid. The frequency domain response of the filter gives us the same information. In addition to the triangular shape of the spectrum, also note the power in the delta function at the carrier frequency (again predicted by the Middleton expansion.) The sampling

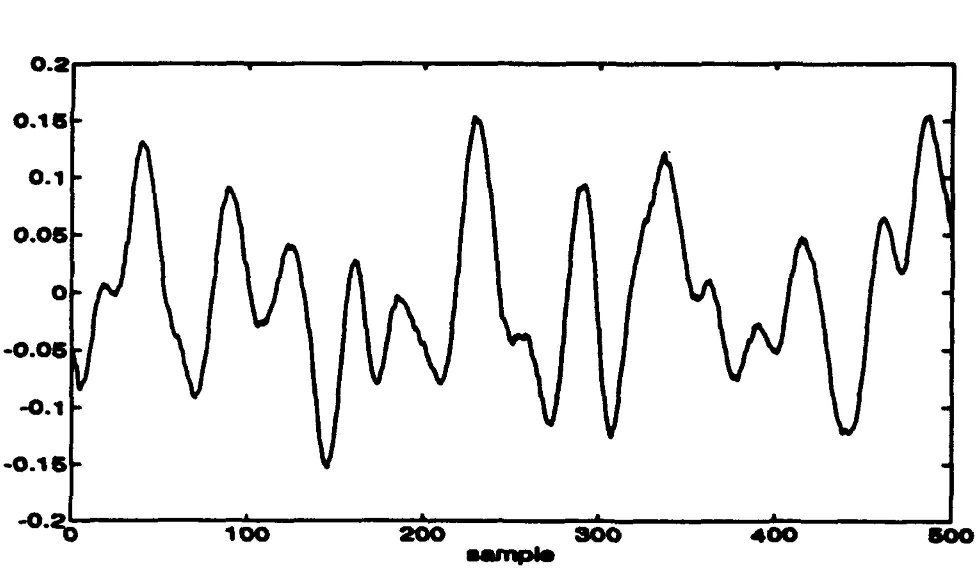


Figure 26. NBFM/LFN Baseband Noise (time samples)

rate chosen to generate the histogram was 25 kS/s, while the sampling rate chosen to generate the sample waveforms was 500 kS/s.

6.1.4 Abnormal Readings. The worst sort of abnormal reading which occurred was the result of a bad match between the actual amplitude of the noise signal being measured and the maximum amplitude range displayed on the oscilloscope. If, for example, the $\pm3\sigma$ band of voltages fell between -2.5 mV and +2.5 mV, and the amplitude display on that channel of the oscilloscope was chosen to be 10 mV/division, then it is clear that almost all voltage samples could fall in half of a single division of the display on the oscilloscope. Since there are eight divisions total on the oscilloscope, when the samples are quantized by the oscilloscope, only a sixteenth of the total quantization levels will be used. This induces a larger quantization error than there needs to be, but, more than that, a reasonably sized variance will cause the NEWTURN.BAS program to produce roughly thirty voltage bins, even though the scope will only pass on the order of 16 distinct voltages to the program in the first place. This results in a situation where roughly half of

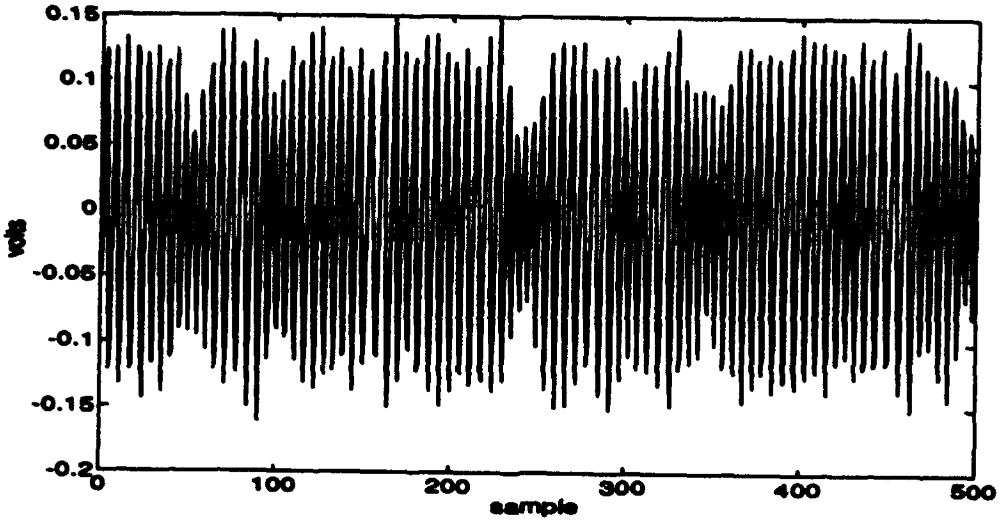


Figure 27. NBFM/LFN Output of IF Filter (time samples)

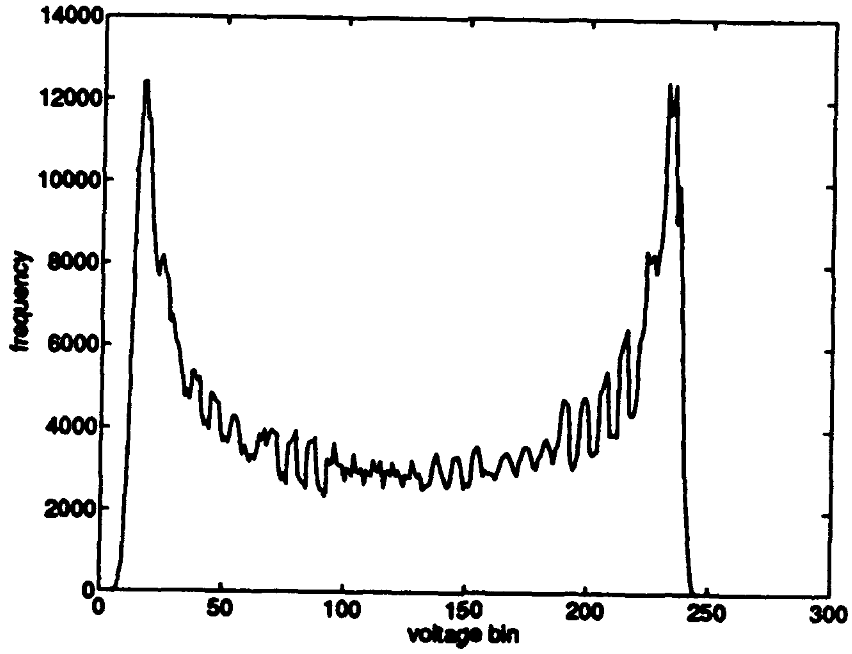


Figure 28. NBFM/LFN Histogram of Time Samples

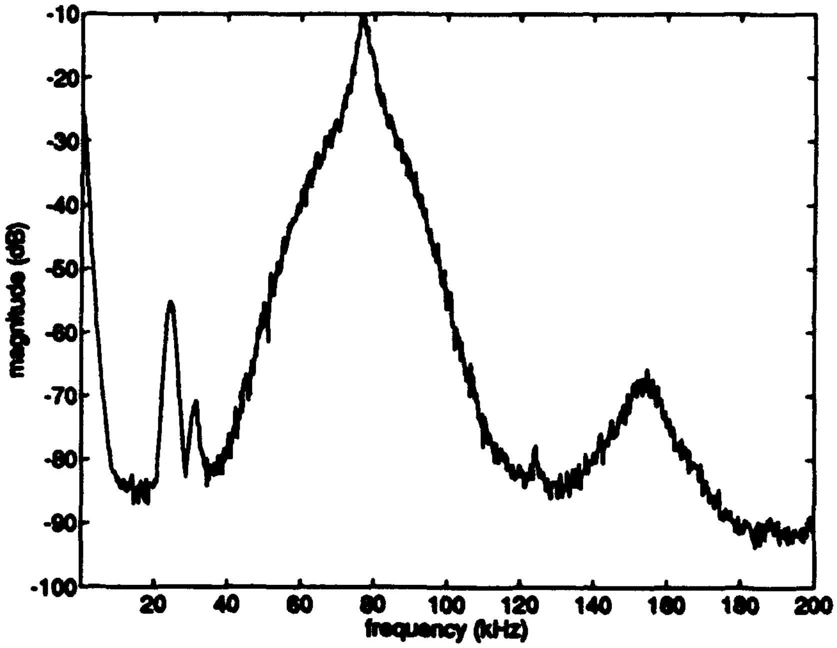


Figure 29. NBFM/LFN Spectrum of Output of IF Filter

the bins which are created absolutely cannot be filled by even a single data point, and the result is a poor TNQ which does not accurately reflect the actual quality of the noise being measured.

This result is reported on for two reasons. First of all, the note which should be taken from this by any future experimenters is simply the common sense assertion that the actual amplitude of the noise signal and the amplitude range of the scope should be reasonably well matched. If anomolous results are obtained which cannot be explained otherwise, this might be something to check. Secondly, some of the data recorded in Appendix B is the result of this kind of bad measurement and it should not be used as if it had a valid relationship to the bandwidth parameters associated with it. Data in the Appendix which is invalid for this reason is clearly marked.

The only other abnormal reading of any consequence was the impulsive nature of the spectrum returned by the spectrum analyzer. Under some circumstances, a single spike in the spectrum would

cause an exceedingly severe frequency-domain penalty to be computed by the IF noise quality program. The suggested solution to this problem is to used FFT-IF noise quality instead.

6.1.5 Problems with the Chi-Square Test. One of the unique features of NEWTURN.BAS is that it performs a chi-square test which either accepts or rejects the hypothesis that the data is normaly distributed. In Daly's thesis, it is asserted that noise produced by WBFM/WBN will pass the chi-squared test. This is true only under some rather specialized circumstances. The chi-square test is fairly sensitive to unevenness in the sample histogram, some of which is caused by the unavoidable quantization error. The effects of this may be smoothed out by lowering the number of voltage bins if the data is fairly gaussian, thus the same set of data points may pass the chi-square test easily if a small number of voltage bins is chosen, but fail it miserably if a large number of bins is chosen.

NEWTURN.BAS does not explicitly choose a larger or smaller number of bins based on the number of samples which are taken, but it does so implicitly because of the dependence of the size of the voltage bins on the variance of the samples and the dependence of the variance of the samples on the number of samples taken, as explained earlier in this chapter. The end result of all this is that when a large number of samples are taken the chi-square test will generally fail, but a small number of samples will sometimes pass. This fact explains the large variance in X^2 recorded in Appendix B.

A number of solutions to this problem are possible, but none are advocated here, primarily because it seems that the application of the chi-square test may be a move in the wrong direction. The question which a noise quality measure tries to answer is not so much, "Is this noise gaussian?" as it is, "How gaussian is this noise?" It is advocated in this thesis and in Daly's thesis that a move in measuring noise quality be made from merely applying a pass/fail criterion to the whiteness of the spectrum toward actually quantifying the whiteness of the spectrum. The application of the chi-square test seems to be a move in the opposite direction: away from quantifying gaussianity,

and toward a mere pass/fail test. For this reason, the problem of properly altering the chi-square test to give consistent results with an increasing number of samples is not considered here.

6.2 Measurements to Explore NBFM/LFN Effect

The NBFM/LFN effect does not, technically speaking, occur in the type of FM/N that would be definitely categorized at NBFM/LFN, rather it occurs in the fuzzy region between WBFM/LFN and NBFM/LFN. Nevertheless, it occurs as a result of a combination of two problems, one of them related to the excess of carrier found in NBFM/N system, and the other of them related to the "dead spaces" found in FM/LFN cases. In order to understand how the effect might arise, and what problem with TNQ it illustrates, consider the following example:

Suppose that a jammer engineer is setting the parameters on his jammer to produce a noise barrage that will jam a 50 kHz receiver. He begins with a baseband noise of 15 kHz and chooses a peak frequency deviation of 200 kHz, to insure that the frequency band of the receiver is well-covered with reasonably white noise. The noise quality that he measures is marginal because he is operating a WBFM/LFN system. What he needs to do to improve his noise quality is to increase the bandwidth of his modulating noise. He would see an improvement from a TNQ of 4 to a TNQ of about 15 if he held his peak frequency deviation constant and increased his baseband noise bandwidth to 50 kHz. However, he finds that if he holds the bandwidth of the modulating noise constant and merely decreases his peak frequency deviation in the direction of NBFM/N, his measurement of TNQ will improve dramatically, up to a point, even while it is becoming increasingly non-white. This may lead him to a mistaken conclusion about the source of his noise quality problems.

This scenario is illustrated in fig 30. The x-axis shows the peak frequency deviation and the y-axis shows the corresponding TNQ. B_m is held constant at 15 kHz, and B_{IF} is held constant at 50 kHz.

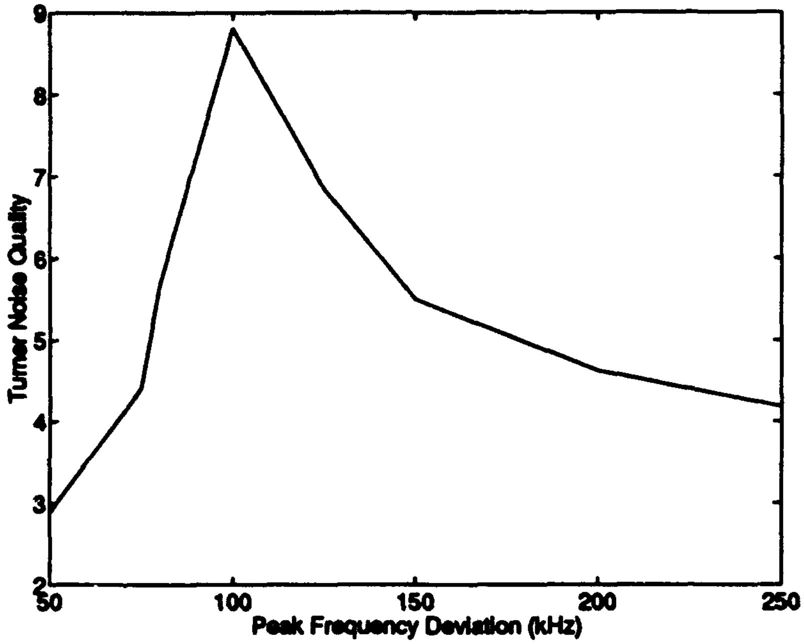


Figure 30. Pathological NBFM/LFN (TNQ vs Δf_p)

A histogram of the data samples at the peak TNQ acheived through this tinkering is shown in figure 31. The effects of both the wide-shoulderedness and the dead spaces are apparent. The tails of the histogram are relatively smooth, and the wideshoulder effect brought them up so that they match the ideal gaussian almost exactly. The only major error introduced (in comparing this histogram to an ideal gaussian) occurs in a few terms around the peak which are obviously much too large. Because of the combination of these effects, the set of samples producing histogram actually have a better TNQ than the baseband noise.

6.3 Measurements of Operational Jammer

The measurements of the operational jammer were taken using a 30 MHz barrage at a center frequency of 6.22 GHz. The barrage was mixed down to an intermediate frequency of either 60 MHz or 20 MHz and passed through filters ranging from .1 MHz up to 6.7 MHz. The noise quality

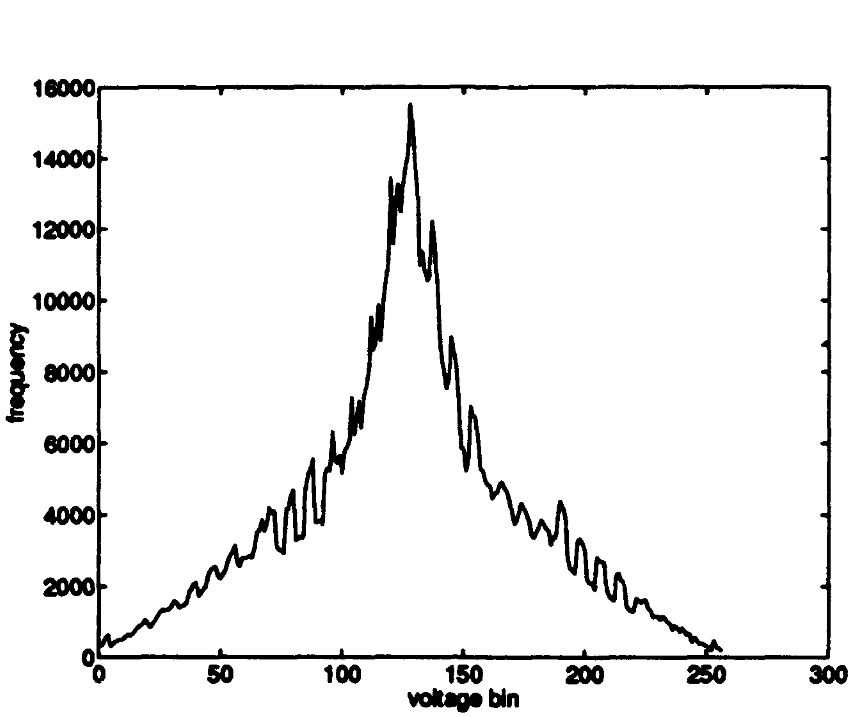


Figure 31. Pathological NBFM/LFN (Histogram at Peak TNQ)

did not vary significantly as the bandwidth of the IF filter was varied, but did vary significantly while the parameters of the system were held constant. A visual observation of the oscilloscope and the frequency analyser showed that the noise produced by the jammer became increasingly impulsive, evidencing the characteristics associated with WBFM/LFN, over a period of about 20 minutes. Later noise quality measurements showed that the noise quality had increased again. This kind of variance may be due to the age of the jammer being tested. The maximum TNQ measured was around 10, while the minimum was less than one.

VII. Conclusions and Recommendations

The new contributions which have been made here to the theory of FM/N (particularly the discussion of the case of NBFM/N) are summarized here. It is concluded that there is a need for a measure of noise quality which quantitatively measures the whiteness as well as the gaussianity of a noise signal, and the solution proposed here is briefly discussed. It is also concluded that the Daly Simulation is a useful tool for experimentally exploring FM/N. Lastly, it is concluded that measurements of operational jammers may be made using commercially available equipment and the techniques developed in the Daly Simulation. In addition to these conclusions, a few reccomendations for future work in this area are presented.

7.1 Conclusions About the Theory of FM/N

One thing that has become increasingly clear throughout this study of FM/N is that the interactions between the three bandwidths involved are highly complex. The most satisfactory theoretical result would be to produce a formula that could give the expected TNQ at the output of a victim receiver when given the TNQ of the baseband noise and the three bandwidths involved. Noting the complications involved in merely solving for the RF spectrum of an FM/N signal when given two bandwidths and assuming ideal gaussian noise led to the conclusion that this kind of result was beyond the scope of this thesis. Short of that goal, what is offered in the way of theory is a set of general observations, similar to those made by Benninghof and Daly, but, hopefully, with more detail and a clearer explanation of the problems that arise under the conditions of NBFM/N.

Essentially, it is concluded that for optimal jamming:

1) B_m should be as large as or a little larger than B_{IF}.

2) Δf_p should be sufficiently large to insure that Woodward's theorem holds, but not much larger.

3) Both WBFM/LFN and NBFM/WBN produce certain characteristic problems that are detrimental to the proper functioning of the jammer. Care should be taken to avoid both of them.

7.2 Conclusions About Noise Quality

The major conclusion about the measurement of noise quality is, as stated above, that there is a need for a measure of noise quality that combines a quantitative measure of whiteness with a quantitative measure of gaussianity. As to how this should be done, the measure presented and implemented here, FFT-IF noise quality, is suggested as one possibility. The features of FFT-IF noise quality that primarily characterize it are as follows:

1) FFT-IF NQ, like TNQ is measured with respect to the particular victim receiver being jammed; thus, multiple systems being compared with each other may be normalized to a common reference.

2) FFT-IF NQ measures gaussianity using the multiple criteria of TNQ which has been extensively experimentally verified.

3) FFT-IF NQ takes into account the effect of the IF filter when measuring the whiteness of the noise being measured.

4) FFT-IF NQ produces a measure which is bounded by 1, thereby making it suitable for insertion into jamming power equations.

These features attempt to draw on the best characteristics of each of the previous noise quality measures that have been proposed. It is hoped any other proposed measures of noise quality which combine a measure of whiteness with a measure of gaussianity would also have these kinds of features.

7.3 Conclusions About the Daly Simulation

There were several limitations encountered in using the Daly Simulation, but the only one which posed any real difficulty was the speed of the computer used to process the data. Forming a histogram which takes adequate advantage of the entire 254 quantization levels of the HP5411D digital oscilloscope requires more than a few thousand samples. This desire to reduce quantization error through developing a valid histogram based on a large number of voltage bins is what led the research team at Stanford to take five million samples to form a histogram (20). The rest of the equipment, although limited in the frequency bands over which it could operate, allowed for the exploration of the full range of FM/N phenomena.

Three suggestions about the Daly Simulation as explained in Daly's thesis are offered:

1) Sampling should be done at a sufficiently slow rate that no data samples need be eliminated.

2) The chi-square test in the program which computes TNQ needs to be altered or eliminated.

3) A faster computer would allow for the processing of more data.

The first suggestion is easy to implement. The third suggestion is easy to implement if there is access to a faster computer. Programs included in this current thesis written in C and Matlab could be used in conjunction with a faster computer to produce results more similar to those obtained by the research team at Stanford. The second suggestion seems like it may be difficult to implement.

7.4 Conclusions About Operational Measurement of Noise Quality

The measurement of an actual radar jammer using the techniques and commercially available measurement equipment of the Daly Simulation has caused the author and sponsor to conclude that measuring the noise quality of operational jammers, or actual jammers under development, is a very real possibility. It has been demonstrated that the programs for measuring noise quality can be successfully translated into the necessary language and installed on any machine supporting

IEEE-488 communication. All that is needed is a jammer and a victim receiver (or simulated receiver, such as the one used by the Stanford team) with which to make standard measurements.

7.5 Recomendations

The recomendations presented here fall into three categories: 1) recomendations for future analysis of FM/N, 2) recomendations for future analysis of noise quality measures, and 3) recomendations for future work with a practical application of the theory of FM/N and noise quality.

As regards future analysis of FM/N, there are two possible avenues of research which were not explored here. The first was the purely theoretical problem of finding any sort of closed form expressions which relate a particular FM/N system to a measure of noise quality, whether TNQ or any of the other measure presented here. Questions such as: "What is the upper bound on TNQ in an FM/N system, given a particular baseband noise TNQ? Under what conditions does that upper bound occur?" might have interesting answers.

The second avenue which has not yet been taken is a complete development of the theory behind FM/S+N, similar to the development of FM/N given here. Such a development should be supported by an experimental set-up which produces FM/S+N and jams a simulated receiver. The results would likely involve more complicated conditional parameters (the frequency of the sinusoid must be varied as well as the bandwidth of the baseband noise) but the results might well be more directly useful to real applications.

As regards future analysis of noise quality measures, there are a continuum of possible approaches that could be taken at this point. At one extreme is the possibility of making an exhaustive comparison of the three IF noise quality measures now available versus a man-in-the-loop jamming simulation. This would ultimately produce graphs, similar to the one developed by the team at Stanford, showing correlations between jammer effectiveness and each of the measures of noise quality. At this point it could be definitively shown which particular noise quality measurements work

best under which circumstances, and how much better they work. Such an exhaustive verification is not necessarily reccomended, but it is offered as a possibility. At the other extreme is purely theoretical research into the theory of measuring parameters of random signals in order to develop a new technique of measuring noise quality superior to any of the techniques so far produced.

A project somewhere between those extremes would be the reworking of the chi-square test in conjuction with some experiments using the Daly Simulation, or simply testing the noise quality measures against each other in a more exhaustive analysis of the possible FM/N scenarios. Because of time limitations, none of the noise quality measures other than TNQ was really adequately experimentally explored, although it is hoped that the theoretical evaluation of the noise quality measures may prove helpful to any future researchers.

Finally, as regards the practical application of the theory of FM/N and noise quality, it is recommended that the testing of operational jammers recommence.

Appendix A. Programs

There are four programs included in this appendix.

The first, 1MEG.C, is written in C and is designed to be used with the AT-GPIB board and to use the NI-488 device level functions to communicate with the HP54111D digital oscilloscope. It reads 125 successive 8 kilobyte traces from channel two of the oscilloscope and sorts them into 256 voltage bins. This data is then recorded to the file OSCOPE.DAT in the format of a list of 256 numbers, the ith number in the list being the number of samples falling in the ith bin. Note that since the numbers are written to the file using the integer format, numbers over 32K will be indicated as negative numbers. The true value is then recovered by addding 64K-1 to any negative numbers.

1MEG.EXE is intended to be used in conjunction with the programs TNQ.M, SMOOTHNQ.M or FFTIFNQ.M in order to produce a histogram that may be compared with a gaussian histogram for the purposes of computing the degree of normality of the data for this reason, it is suggested that the sampling rate on the oscilloscope be lowered sufficiently that all samples are uncorrelated.

The second program, TDDATA.C is also written in C and is designed to take samples from the HP54111D oscilloscope. However, it takes simultaneous samples from channels one and two of the oscilloscope and it only takes a single 8 kilobyte trace from each channel. There are two intended uses for TDDATA.C. The first is that it be used in conjunction with the program FFTIT.M in order to compute the whiteness of the noise being sampled. In this case it should be modified to discard all but the first 1000 samples of channel two and write the channel two to the file OSCOPE.DAT as a series of samples, followed by the data necessary for the D/A conversion.

The second is that it be used in conjunction with a simple plotting program written in Matlab to generate simulataneous plots of baseband noise and noise at the IF filter output for purposes of comparison. In this case, it should be modified to discard all but the first 500 samples of both channel one and channel two and write first channel one, followed by the D/A conversion data for

channel one and then channel two, followed by the D/A conversion data for channel two, to the file PLT.DAT.

In both cases the sampling rate on the oscilloscope should be significantly greater than the Nyquist rate, so that the waveforms will show up clearly and so that a proper estimation of the spectrum may be made.

The third program TNQ.M is written in matlab. It reads the data produced by 1MEG.EXE and produces a plot of the histogram along with a plot of an ideal gaussian with the same mean and variance. It also implements the measurement of noise quality developed by Ottoboni, Turner and others.

The fourth program, SMOOTHNQ.M, is also written in matlab. It reads the data produced by 1MEG.EXE and produces a modified histogram by combining a number of voltage bins based on the size of the parameter F. It computes a smoothed "Turner Noise Qaulity" similar to the noise quality measure employed by Daly in his program NEWTURN.BAS.

```
/*
 * Written in:   Microsoft C
 * File name:  1Meg.C
 * Written by: Tim Taylor, Nov 1993
 *
 * This program uses the function GPIBERR which was included in the
 * documentation with the NI-488 AT-GPIB board, and is designed to use
 * the NI-488 device level functions. This program must be linked with
 * MCIB.OBJ in order to compile properly.
 */
```

```
/* ==========================================================================
 * DEV1 in the configuration program IBCONF has been renamed to DEVA.
 *
 * This program reads 1 Meg of samples from channel 2 of the HP54111D
 * digital oscilloscope and then sorts them into 256 voltage bins. It then
 * writes the contents of the voltage bins in terms of samples per bin
 * to a file named 'ocsope.dat'. It also finds the yref, yinc,  and yorg
 * which are necessary to calculate the absolute values of the data samples
 * and it writes these values to the end of 'oscope.dat'
 *
 * The function GPIBERR is called when a NI-488 function fails.  The
 * error message is printed along with the status variables IBSTA, IBERR,
 * and IBCNT.  GPIBERR is found in the documentation on NI-488, and the
 * error variables are defined in DECL.H
 *
 * The NI-488 function IBONL is called from the main body of the program or
 * from the functions GPIBERR.   When the second parameter
 * of the function IBONL is zero, the software and hardware are disabled.
 *
 * The function EXIT is used to terminate this program within the function
 * GPIBERR.  The exit status is set to 1 to indicate an error has occured.
 * ==========================================================================
 */

#include <stdio.h>
#include <stdlib.h>
```

```
#include <string.h>
#include <math.h>
#include "decl.h"

void gpiberr(char *msg);

  unsigned char  rd[8196],          /* read byte data buffer         */
                 exp_string[13];    /* read exponent data buffer     */
  int            dvm,               /* device number                 */
                 bins[256],         /* voltage bins                  */
                 m,i;               /* FOR loop counter              */
  double         sum;               /* Accumulator of measurements   */
  float          yref,              /* YREFERENCE                    */
                 yinc,              /* YINCREMENT                    */
                 yorg;              /* YORIGIN                       */
  FILE           *outfile;          /* pointer to file for output    */

void main() {

   system("cls");

   printf("blank screen on the hp54111 oscope");
   printf("\n");

/*
 * "DEVA" is the name configured for the HP5411D using IBCONF.EXE
```

```
 * If DEVA is less than zero, call GPIBERR with an error message.
 */

   dvm = ibfind ("DEVA");
   if (dvm < 0) gpiberr("ibfind Error");

/*
 * Blank the screen on the hp54111d oscope and prepare to receive data
 * in BYTE format.
 * If the error bit ERR is set in IBSTA, call GPIBERR with an error message.
 */

   ibwrt (dvm,"ACQUIRE TYPE NORMAL",19L);
   ibwrt (dvm,"ACQUIRE RESOLUTION OFF",22L);
   ibwrt (dvm,"WAVEFORM SOURCE MEMORY 2",24L);
   ibwrt (dvm,"WAVEFORM FORMAT BYTE",21L);
   ibwrt (dvm,"BLANK CHANNEL 1",15L);
   ibwrt (dvm,"BLANK CHANNEL 2",15L);
   if (ibsta & ERR) gpiberr("ibwrt Error");

/* initialize voltage bins                                              */

   for (i=0;i<256;i++){
       bins[i] = 0;
   };
```

```
/*  begin loop to obtain data.  Note: 125 x 8K = 1M                      */

    for (m=0;m<125;m++){
        printf("reading dump #%d\n",m);

/*      obtain 8192 voltage samples.                                    */

        ibwrt(dvm,"DIGITIZE CHANNEL 2",18L);
        ibwrt(dvm,"DATA?",5L);
        ibrd (dvm,rd,8196L);

/* sort data into voltage bins                                          */

        for (i=4;i<8196;i++){
            bins[rd[i]]++;
        };
    };

/*  open file 'oscope.dat' to write data to                              */

    outfile = fopen("oscope.dat","w");
    for (i=0;i<256;i++){
        fprintf(outfile,"%d\n",bins[i]);
    };

    printf("\n Done reading data \n");
```

```
/*  read yref from HP54111D                                    */

    ibwrt (dvm,"YREFERENCE?",11L);
    ibrd (dvm, exp_string, 6L);
    exp_string[6] = '\n';
    printf("The yreference returned was: ");
    for (m = 0;m<12;m++){
       printf("%c",exp_string[m]);
    };
    printf("\n");
    yref = atof (exp_string);
    fprintf(outfile,"%f\n",yref);

/*  read yinc from HP54111D                                    */

    ibwrt (dvm,"YINCREMENT?",11L);
    ibrd (dvm, exp_string, 12L);
    exp_string[12] = '\n';
    printf("The yincrement returned was: ");
    for (m = 0;m<12;m++){
       printf("%c",exp_string[m]);
    };
    printf("\n");
    yinc = atof (exp_string);
    fprintf(outfile,"%E\n",yinc);
```

```
/*  read yorg from HP54111D                                          */


    ibwrt (dvm,"YORIGIN?",8L);

    ibrd (dvm, exp_string, 12L);

    exp_string[12] = '\n';

    printf("The origin returned was: ");

    for (m = 0;m<12;m++){

       printf("%c",exp_string[m]);

    };

    printf("\n");

    yorg = atof (exp_string);

    fprintf(outfile,"%E\n",yorg);


/*  return oscilloscope to normal operation and relinquish control   */


    ibwrt (dvm,"VIEW CHANNEL 1",14L);

    ibwrt (dvm,"VIEW CHANNEL 2",14L);

    ibwrt (dvm,"LOCAL",5L);


/*  close data file                                                  */


    fclose(outfile);


/*  Call the ibonl function to disable the hardware and software.    */
```

```
    ibonl (dvm,0);

}

/* ========================================================================
 *                          Function GPIBERR
 * This function will notify you that a NI-488 function failed by
 * printing an error message.  The status variable IBSTA will also be
 * printed in hexadecimal along with the mnemonic meaning of the bit position.
 * The status variable IBERR will be printed in decimal along with the
 * mnemonic meaning of the decimal value.  The status variable IBCNT will
 * be printed in decimal.
 *
 * The NI-488 function IBONL is called to disable the hardware and software.
 *
 * The EXIT function will terminate this program.
 * ========================================================================
 */

void gpiberr(char *msg) {

    printf ("%s\n", msg);

    printf ("ibsta = &H%x  <", ibsta);
    if (ibsta & ERR )  printf (" ERR");
    if (ibsta & TIMO)  printf (" TIMO");
```

```
if (ibsta & END ) printf (" END");
if (ibsta & SRQI) printf (" SRQI");
if (ibsta & RQS ) printf (" RQS");
if (ibsta & SPOLL) printf (" SPOLL");
if (ibsta & EVENT) printf (" EVENT");
if (ibsta & CMPL) printf (" CMPL");
if (ibsta & LOK ) printf (" LOK");
if (ibsta & REM ) printf (" REM");
if (ibsta & CIC ) printf (" CIC");
if (ibsta & ATN ) printf (" ATN");
if (ibsta & TACS) printf (" TACS");
if (ibsta & LACS) printf (" LACS");
if (ibsta & DTAS) printf (" DTAS");
if (ibsta & DCAS) printf (" DCAS");
printf (" >\n");

printf ("iberr = %d", iberr);
if (iberr == EDVR) printf (" EDVR <DOS Error>\n");
if (iberr == ECIC) printf (" ECIC <Not CIC>\n");
if (iberr == ENOL) printf (" ENOL <No Listener>\n");
if (iberr == EADR) printf (" EADR <Address error>\n");
if (iberr == EARG) printf (" EARG <Invalid argument>\n");
if (iberr == ESAC) printf (" ESAC <Not Sys Ctrlr>\n");
if (iberr == EABO) printf (" EABO <Op. aborted>\n");
if (iberr == ENEB) printf (" ENEB <No GPIB board>\n");
if (iberr == EOIP) printf (" EOIP <Async I/O in prg>\n");
```

```
    if (iberr == ECAP) printf (" ECAP <No capability>\n");
    if (iberr == EFSO) printf (" EFSO <File sys. error>\n");
    if (iberr == EBUS) printf (" EBUS <Command error>\n");
    if (iberr == ESTB) printf (" ESTB <Status byte lost>\n");
    if (iberr == ESRQ) printf (" ESRQ <SRQ stuck on>\n");
    if (iberr == ETAB) printf (" ETAB <Table Overflow>\n");

    printf ("ibcnt = %d\n", ibcnt);
    printf ("\n");

/*  Call the ibonl function to disable the hardware and software.          */

    ibonl (dvm,0);

    exit(1);
}

/*
 *  Written in: Microsoft C
 *  File name:  TDDATA.C
 *  Written by: Tim Taylor, Nov 1993
 *
 *  The function GPIBERR (found in the documentation included with the AT-GPIB
 *  package) must be included at the end of this program if it is to compile
 *  properly. The file MCIB.OBJ, which is included with the AT-GPIB package must be
 *  linked with this file in order for it to compile properly.
```

```
*
*  This program is designed to read 8192 data points from the HP5411D
*  digital oscilloscope from each of channel one and two and retain only
*  the first 500 of them from each channel. This data, along with
*  the data necessary for a D/A conversion, is then written
*  to the file plt.dat where it can be read into matlab to produce
*  plots of the waveform. Or to be used in conjuction with
*
*  Other comments concerning the function of this program in conjunction
*  with the AT-GPIB board can be found in the comments section of 1MEG.C
*
*/

#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <math.h>
#include "decl.h"

void gpiberr(char *msg);

 unsigned char  rd1[8196],              /* read byte data buffer ch1      */
         rd2[8196],                     /* read byte data buffer ch2      */
         exp_string[13];                /* read exponent data buffer      */
 int     dvm,                           /* device number                  */
         m,i;                           /* FOR loop counter               */
```

```
  double   sum;                    /* Accumulator of measurements    */
  float    yref,                   /* YREFERENCE                     */
           yinc,                   /* YINCREMENT                     */
           yorg;                   /* YORIGIN                        */
  FILE     *outfile;               /* pointer to file for output     */

void main() {

    system("cls");
    printf("blank screen on the hp54111 oscope");
    printf("\n");

/*
 *  "DEVA" is the name configured for the HP5411D using IBCONF.EXE
 *  If DEVA is less than zero, call GPIBERR with an error message.
 */

    dvm = ibfind ("DEVA");
    if (dvm < 0) gpiberr("ibfind Error");

/*
 *  Blank the screen on the hp54111d oscope and prepare to receive data
 *  in BYTE format.
 *  If the error bit ERR is set in IBSTA, call GPIBERR with an error message.
 */
```

```
    ibwrt (dvm,"ACQUIRE TYPE NORMAL",19L);
    ibwrt (dvm,"ACQUIRE RESOLUTION OFF",22L);
    ibwrt (dvm,"WAVEFORM FORMAT BYTE",21L);
    ibwrt (dvm,"BLANK CHANNEL 1",15L);
    ibwrt (dvm,"BLANK CHANNEL 2",15L);
    if (ibsta & ERR) gpiberr("ibwrt Error");

        printf("reading data\n");


/*  open file 'plt.dat' to write data to                    */

    outfile = fopen("plt.dat","w");

/*      obtain channel 1 data samples.                      */

        ibwrt(dvm,"DIGITIZE CHANNEL 1,2",20L);
        ibwrt (dvm,"WAVEFORM SOURCE MEMORY 1",24L);
        ibwrt(dvm,"DATA?",5L);
        ibrd (dvm,rd1,8196L);

    for (i=4;i<504;i++){
        fprintf(outfile,"%d\n",rd1[i]);
    };

/*  read yref for channel 1 from HP54111D                   */
```

```
    ibwrt (dvm,"YREFERENCE?",11L);
    ibrd (dvm, exp_string, 6L);
    exp_string[6] = '\n';
    printf("The yreference returned was: ");
    for (m = 0;m<12;m++){
       printf("%c",exp_string[m]);
    };
    printf("\n");
    yref = atof (exp_string);
    fprintf(outfile,"%f\n",yref);

/*  read yinc from HP5411D                                          */

    ibwrt (dvm,"YINCREMENT?",11L);
    ibrd (dvm, exp_string, 12L);
    exp_string[12] = '\n';
    printf("The yinc returned was: ");
    for (m = 0;m<12;m++){
       printf("%c",exp_string[m]);
    };
    printf("\n");
    yinc = atof (exp_string);
    fprintf(outfile,"%E\n",yinc);

/*  read yorg from HP5411D                                          */
```

```
    ibwrt (dvm,"YORIGIN?",8L);

    ibrd (dvm, exp_string, 12L);

    exp_string[12] = '\n';

    printf("The origin returned was: ");

    for (m = 0;m<12;m++){

       printf("%c",exp_string[m]);

    };

    printf("\n");

    yorg = atof (exp_string);

    fprintf(outfile,"%E\n",yorg);


/*      obtain channel 2 data samples.                                   */


        ibwrt (dvm,"WAVEFORM SOURCE MEMORY 2",24L);

        ibwrt(dvm,"DATA?",5L);

        ibrd (dvm,rd2,[illegible]96L);


    for (i=4;i<504;i++){

        fprintf(outfile,"%d\n",rd2[i]);

    };



/*  read yref for channel 2 from HP54111D                                */


    ibwrt (dvm,"YREFERENCE?",11L);
```

```
    ibrd (dvm, exp_string, 6L);
    exp_string[6] = '\n';
    printf("The yreference returned was: ");
    for (m = 0;m<12;m++){
       printf("%c",exp_string[m]);
    };
    printf("\n");
    yref = atof (exp_string);
    fprintf(outfile,"%f\n",yref);

/*  read yinc from HP54111D                                          */

    ibwrt (dvm,"YINCREMENT?",11L);
    ibrd (dvm, exp_string, 12L);
    exp_string[12] = '\n';
    printf("The yinc returned was: ");
    for (m = 0;m<12;m++){
       printf("%c",exp_string[m]);
    };
    printf("\n");
    yinc = atof (exp_string);
    fprintf(outfile,"%E\n",yinc);

/*  read yorg from HP54111D                                          */

    ibwrt (dvm,"YORIGIN?",8L);
```

```
    ibrd (dvm, exp_string, 12L);
    exp_string[12] = '\n';
    printf("The origin returned was: ");
    for (m = 0;m<12;m++){
       printf("%c",exp_string[m]);
    };
    printf("\n");
    yorg = atof (exp_string);
    fprintf(outfile,"%E\n",yorg);

    printf("\n Done reading data \n");

/*  return oscilloscope to normal operation and relinquish control       */

    ibwrt (dvm,"VIEW CHANNEL 1",14L);
    ibwrt (dvm,"VIEW CHANNEL 2",14L);
    ibwrt (dvm,"LOCAL",5L);

/*  close data file                                                       */

    fclose(outfile);

/*  Call the ibonl function to disable the hardware and software.        */

    ibonl (dvm,0);
```

```
}



%
%   tnq.m
%   written by Tim Taylor in Matlab, November 1993
%   designed to function in connection with the program 1MEG.EXE
%   which will read 1 Meg of data points from a digitizing oscilloscope
%   with 254 quantization levels, and sort them into voltage bins
%   corresponding to those levels, and place the number of hits in each
%   bin in a file ''oscope.dat'' where it can be read by matlab.
%

!1MEG
N = 256;
P = 8192 * 125;
n = 1:N ;
load oscope.dat
pdf = oscope(n) ;
yref = oscope(257) ;
yinc = oscope(258) ;
yorg = oscope(259) ;
trueval = (n-yref)*yinc + yorg ;
for i = 1:N
    if pdf(i) < 0
       pdf(i) = pdf(i) + 65526;
```

```
    end
end
sum = 0;
sum2 = 0;
variance = 0;
variance2 = 0;
skewness = 0;
kurtosis = 0;
for i=1:N
    sum = sum + pdf(i)*trueval(i);
    sum2 = sum2 + pdf(i)*i;
end
mean = sum/P;
mean2 = sum2/P;
for i=1:N
    dif2 = i - mean2;
    dif = trueval(i)-mean;
    variance2 = variance2 + pdf(i)*dif2^2;
    variance = variance + pdf(i)*dif^2;
    skewness = skewness + pdf(i)*dif2^3;
    kurtosis = kurtosis + pdf(i)*dif2^4;
end
variance = variance/P
variance2 = variance2/P;
sigma = variance^(.5)
sigma2 = variance2^(.5);
```

```
skewness = skewness/(P*sigma2^3);

kurtosis = kurtosis/(P*variance2^2);


e = -2*variance2;

c = sigma2*(2*pi)^.5;

ln2 = log(2);

es = 0;

Hg = 0;

H = 0;

for i=1:N

    dif = i-mean2;

    gpdf(i) = P*(exp(dif^2/e)/c);

    es = es + abs(gpdf(i)-pdf(i));

    Hg = Hg + (1/P)^2 * gpdf(i) * log(gpdf(i))/ln2 ;

    if pdf(i) > 0

       H = H + (1/P)^2 * pdf(i) * log(pdf(i))/ln2 ;

    end

end

Hr = abs(Hg - H);

es = es/P

binl = 1;

binh = N;

for i=1:N;

  if i < (mean2-3*sigma2)

     binl = i;

  end
```

```
end
for i=N:-1:1
  if i > (mean2+3*sigma2)
     binh = i;
  end
end
esum1 = 0;
esum2 = 0;
m = binh-binl+1;
for i = binl:binh;
    esum1 = esum1 + abs(pdf(i)-gpdf(i))/gpdf(i);
    esum2 = esum2 + ((pdf(i)-gpdf(i))/gpdf(i))^2;
end
ea = esum1/m;
er = (esum2/m)^.5;
term1 = (1/3)*(ea+es+er);
term2 = Hr;
term3 = (1/2)*(abs(kurtosis-3) + abs(skewness));
TNQ = 3/(term1 + term2 + term3)

plot (n,pdf)
hold on
plot (n,gpdf)
pause
hold off
```

```
%   smoothnq.m
%   written by Tim Taylor in Matlab, November 1993
%   designed to function in connection with the program 1MEG.EXE
%   which will read 1 Meg of data points from a digitizing oscilloscope
%   with 254 quantization levels, and sort them into voltage bins
%   corresponding to those levels, and place the number of hits in each
%   bin in a file ''oscope.dat'' where it can be read by matlab.
%   Differs from tnq.m in that it combines groups of voltage bins
%   to get a smoother pdf.
%

!1MEG
N = 256;
P = 8192 * 125;
n = 1:N ;

F = 8;
N2 = N/F;
n2 = 1:N2;
spdf = 1:N2;
for i = 1:N2
    spdf(i) = 0;
end

load oscope.dat
```

```
pdf = oscope(n) ;
yref = oscope(257) ;
yinc = oscope(258) ;
yorg = oscope(259) ;
trueval = (n-yref)*yinc + yorg ;
for i = 1:N
    if pdf(i) < 0
       pdf(i) = pdf(i) + 65526;
    end
end

for i = 1:N2
    tmp = (i-1)*F;
    for j = 1:F
        tmp2 = j + tmp;
        spdf(i) = spdf(i) + pdf(tmp2);
    end
end

sum = 0;
sum2 = 0;
variance = 0;
variance2 = 0;
skewness = 0;
kurtosis = 0;
for i = 1:N
```

```
    sum = sum + pdf(i)*trueval(i);
end
for i=1:N2
    sum2 = sum2 + spdf(i)*i;
end
mean = sum/P;
mean2 = sum2/P;
for i=1:N
    dif = trueval(i)-mean;
    variance = variance + pdf(i)*dif^2;
end
for i=1:N2
    dif2 = i - mean2;
    variance2 = variance2 + spdf(i)*dif2^2;
    skewness = skewness + spdf(i)*dif2^3;
    kurtosis = kurtosis + spdf(i)*dif2^4;
end
variance = variance/P
variance2 = variance2/P;
sigma = variance^(.5)
sigma2 = variance2^(.5);
skewness = skewness/(P*sigma2^3);
kurtosis = kurtosis/(P*variance2^2);

e = -2*variance2;
c = sigma2*(2*pi)^.5;
```

```
ln2 = log(2);
es = 0;
H = 0;
Hg = 0;
for i=1:N2
    dif = i-mean2;
    gpdf(i) = P*(exp(dif^2/e)/c);
    es = es + abs(gpdf(i)-spdf(i));
    Hg = Hg +(1/P)^2 * gpdf(i) * log(gpdf(i))/ln2 ;
    if spdf(i) > 0
       H = H + (1/P)^2 * spdf(i) * log(spdf(i))/ln2 ;
    end
end
Hr = abs(H - Hg);
es = es/P;
binl = 1;
binh = N2;
for i=1:N2;
  if i < (mean2-3*sigma2)
     binl = i;
  end
end
for i=N2:-1:1
  if i > (mean2+3*sigma2)
     binh = i;
  end
```

```
end
esum1 = 0;
esum2 = 0;
m = binh-binl
for i = binl:binh
    esum1 = esum1 + abs(spdf(i)-gpdf(i))/gpdf(i);
    esum2 = esum2 + ((spdf(i)-gpdf(i))/gpdf(i))^2;
end
ea = esum1/m;
er = (esum2/m)^.5;
term1 = (1/3)*(ea+es+er);
term2 = Hr;
term3 = (1/2)*(abs(kurtosis-3) + abs(skewness));
STNQ = 3/(term1 + term2 + term3)


plot (n2,spdf)
hold on
plot (n2,gpdf)
pause
hold off
```

Appendix B. Data

This appendix includes all the data taken in the course of the experimental work described in this thesis in a tabular format.

There are three sections in this appendix, each section corresponding to one of the three types of experiments performed. At the beginning of each section, (or each subsection, if there are subsections), there is a table which describes the general setup used to obtain the data, in terms of settings on each of the experimental devices used as described in Chapter 5. Typical parameters specified are: 1) the file name of the program used to process the data and any comments about modifications to the program, 2) the position of the peak frequency deviation switch and the actual peak frequency deviation, 3) the output rms amplitude and the bandwidth of the modulating noise generator, 4) the upper and lower bandwidths chosen on the simulated victim receiver filter, and 5) the sampling rate and volts/division chosen on the oscilloscope.

The following tables in each section will note any slight parameter modifications and go on to list the noise quality measurements (TNQ or IFNQ) and any other data which was collected at the same time (such as mean, variance, maximum voltage, minimum voltage, number of bins chosen, chi-square test parameters, etc.)

Unless otherwise noted, the center frequency of the FM modulator was chosen to be 250MHz + $(1/2) \cdot (f_{hi} - f_{lo})$ while the signal generator which acted as the local oscillator was held at 250 MHz. Furthermore, the rms output of each of the signal generators was held at 0dB. Settings of the baseband noise generator other than the rms output level and the noise bandwidth can be found in Chapter 4 of (8). Samples of the baseband noise were usually taken from channel one of the oscilloscope, while samples of the signal at the output of the IF filter were taken from channel two of the oscilloscope.

Table 5. Settings to Unintentionally Correlate Data

Program Used	
File Name:	NEWTURN.BAS
Comment:	Bug In
Noise Generator Settings	
RMS Amplitude	B_m
1 Vrms	50 kHz
FM Modulator Settings	
Peak Dev. Switch	Δf_p
1.28 MHz	150 kHz
IF Filter Settings	
f_{lo}	f_{hi}
65 kHz	101.5 kHz
Oscilloscope Settings	
Sampling Rate	Volts/Division
500 KS/s	10 mV

B.1 Data from Daly Simulation

B.1.1 Effects of a Small Sample of Unintentionally Correlated Data. The first set of data was obtained using the set-up given in table 5 and merely attempted to duplicate one of the experiments described in Daly's thesis as carefully as possible. The comment under Program Used of "Bug In" merely indicates that the error which caused the data samples to remain correlated was left in. The corresponding data is found in table 6 and table 7 where the only difference between the two tables is the number of data points collected. Note that the TNQ goes down as the number of samples is decreased seemingly indicating that the noise is of a worse quality, but X^2 also decreases, making it more likely that the chi-square test will be passed. This is due to the decrease in the number of voltage bins, as explained in Chapter 6.

B.1.2 Effects of a Small Sample of Uncorrelated Data. The second set of data used a setup identical to the first with the exception that the error was removed. The setup is recorded in table 8 The corresponding data is recorded in table 9 and table 10, the difference between the two tables being the number of points which were taken.

Table 6. Noise Quality of 3277 Unintentionally Correlated Samples

3277 Samples Used			
Measurement	TNQ	X^2	σ^2
1	9.4432	43	.0049
2	6.8632	116	.0052
3	8.0408	97.86	.0050
4	6.0353	171.27	.0052
5	8.7239	72.45	.0050
6	8.7638	84.6	.0050
7	7.4135	99.76	.0051
8	6.5725	136.53	.0052
9	8.0434	77.24	.0050
10	7.3541	116.27	.0051
11	8.4738	85.09	.0049
12	7.5004	99.54	.005
13	7.3063	82.34	.0051
14	6.6706	144.03	.0053
15	8.6235	115	.005
averages			
	7.75	102.7	.005

Table 7. Noise Quality of 1490 Unintentionally Correlated Samples

3277 Samples Used			
Measurement	TNQ	X^2	σ^2
1	7.4513	64.11	.0044
2	7.4385	38.24	.0041
3	7.7845	38.57	.0044
4	7.8437	37.65	.0043
5	6.3693	54.87	.0047
6	5.5191	64.95	.0045
7	6.7796	47.81	.0043
8	7.3317	31.22	.0044
9	5.6599	76.94	.0045
10	7.0322	38.27	.0043

Table 8. Settings to Decorrelate Data

Program Used	
File Name:	NEWTURN.BAS
Comment:	Bug Removed
Noise Generator Settings	
RMS Amplitude	B_m
1 Vrms	50 kHz
FM Modulator Settings	
Peak Dev. Switch	Δf_p
1.28 MHz	150 kHz
IF Filter Settings	
f_{lo}	f_{hi}
65 kHz	101.5 kHz
Oscilloscope Settings	
Sampling Rate	Volts/Division
500 KS/s	10 mV

3277 Samples Used			
Measurement	TNQ	X^2	σ^2
1	8.0434	72.74	.005
2	8.833	82.22	.0050
3	7.2628	131	.0050
4	9.514	63.9	.0052
5	8.0452	91.84	.0047
6	7.0096	103.97	.0051
7	8.0093	120.17	.0049
8	7.4013	92.85	.0051
9	7.6061	103.02	.005
10	7.8529	106.94	.005
11	6.8537	100.8	.0049
12	9.14	144.7	.005
13	8.4715	105.49	.0051
14	10.399	83.02	.0053
15	8.0003	102.99	.005

Table 9. Noise Quality of Uncorrelated Data

Table 10. Noise Quality of 1490 Unintentionally Correlated Samples

1490 Samples Used			
Measurement	TNQ	X^2	σ^2
1	7.056	56.36	.0044
2	7.8911	38.65	.0044
3	6.2469	60.84	.0043
4	7.7844	55.44	.0044
5	8.193	46.32	.0045
6	7.7418	54.05	.0043
7	7.7447	40.38	.0045
8	5.9585	58.81	.0043
9	7.8464	40.22	.0043
10	8.3697	25.49	.0036

Table 11. Mismatched Volt/div Setting

Program Used	
File Name:	NEWTURN.BAS
Comment:	Bug Removed
Noise Generator Settings	
RMS Amplitude	B_m
1 Vrms	50 kHz
FM Modulator Settings	
Peak Dev. Switch	Δf_p
1.28 MHz	150 kHz
IF Filter Settings	
f_{lo}	f_{hi}
65 kHz	101.5 kHz
Oscilloscope Settings	
Sampling Rate	Volts/Division
500 KS/s	80 mV

B.1.3 Anomolous results of poor choice of Volt/div setting. The third set of data used a setup identical to the second with the exception that a Volt/div setting on the oscilloscope which was poorly matched to the amplitude of the signal was chosen. The setup is recorded in table 11 The corresponding data is recorded in table 12 and table 13, the difference between the two tables being the number of points which were taken. Note that X^2 values are unreasonably large and TNQ is unreasonably small for the WBFM/WBN scenario, due to gaps in the histogram resulting from poor use of the oscilloscope.

Table 12. Noise Quality With Mismatched Volt/div Setting1

1490 Samples Used			
Measurement	TNQ	X^2	σ^2
1	1.1903	1933.88	.0054
2	1.1607	1980.51	.0053
3	1.1237	1831.5	.0056
4	1.2379	1927.45	.0055
5	1.25	1861	.0056

Table 13. Noise Quality With Mismatched Volt/div Setting2

3277 Samples Used			
Measurement	TNQ	X^2	σ^2
1	1.2128	4217.47	.0056
2	1.1738	4456.67	.0054
3	1.2184	3968.44	.0055
4	1.2006	4294.09	.0055
5	1.2073	4213.64	.0054

B.1.4 Increased sample set. The fourth group of experiments explored the possibility of taking a larger group of uncorrelated samples than had been attempted with the original Daly Simulation. The program was modified so that no samples were discarded, 16384 samples were taken, and the change caused by slowing reducing the sample rate so that data was decorrelated was investigated. The setup is shown in table 14. The data is shown in table 15, table 16 and table 17 where the difference in each table is the sampling rate of the oscilloscope. The number of samples was finally increased to 24576 (the maximum possible with the program NEWTURN.BAS substantially unaltered) and the sampling rate was reduced to 50 KS/s. The results of this are shown in table 18. Note that in all these cases X^2 was far too large to pass the chi-square test, but the TNQ remained relatively stable within the range we had come to expect by this point.

B.1.5 The Central Limit Theorem. After the first experiments using the Daly Simulation, it was concluded that the proper technique for using the simulation was to eliminate the part of NEWTURN.BAS that discarded excess samples and to sample at a rate that would leave the data uncorrelated. Once this was done, settings were chosen to explore the effect of decreasing the IF bandwidth to demonstrate the Central Limit Theorem. The settings are shown in table 19. The

Table 14. Increased Sample Set Setting

Program Used	
File Name:	NEWTURN.BAS
Comment:	No Samples Discarded
Noise Generator Settings	
RMS Amplitude	B_m
1 Vrms	50 kHz
FM Modulator Settings	
Peak Dev. Switch	Δf_p
1.28 MHz	150 kHz
IF Filter Settings	
f_{lo}	f_{hi}
65 kHz	101.5 kHz
Oscilloscope Settings	
Sampling Rate	Volts/Division
50 KS/s	10 mV

Table 15. Increased Sample Set Data Setting1

500 KS/s			
Measurement	TNQ	X^2	σ^2
1	7.9761	485.56	.0044
2	8.0119	504.16	.0042
3	7.9962	321.85	.0043
4	8.9549	583.26	.0044
5	9.5233	517.58	.0043

Table 16. Increased Sample Set Data Setting2

250 KS/s			
Measurement	TNQ	X^2	σ^2
1	8.4741	430.51	.0050
2	7.3876	492.93	.0049
3	9.4624	387.14	.0049
4	8.5899	314.86	.0050
5	8.837	329.41	.0050

Table 17. Increased Sample Set Data Setting3

100 KS/s			
Measurement	TNQ	X^2	σ^2
1	9.437	237.11	.0044
2	7.8714	467.64	.0042
3	7.968	495.19	.0042
4	8.3558	555.76	.0043
5	7.1931	772.1	.0042

Table 18. Increased Sample Set Data Setting4

50 KS/s			
Measurement	TNQ	X^2	σ^2
1	8.8938	483.7	.0018
2	9.7156	329.57	.0018
3	8.8891	426.17	.0018
4	7.6657	434.88	.0018
5	9.8168	368.25	.0018

Table 19. Settings to Demonstrate CLT

Program Used	
File Name:	NEWTURN.BAS
Comment:	No Samples Discarded
Noise Generator Settings	
RMS Amplitude	B_m
1 Vrms	50 kHz
FM Modulator Settings	
Peak Dev. Switch	Δf_p
1.28 MHz	150 kHz
IF Filter Settings	
f_{lo}	f_{hi}
variable	110 kHz
Oscilloscope Settings	
Sampling Rate	Volts/Division
variable	10 mV

corresponding data is shown in table 20, table 21, table 22 table 23, and table 24 where the only change from one table to the next is the bandwidth of the IF filter and the sampling rate chosen.

B.2 Pathological NBFM/LFN Measurements

In this section the data which was taken to demonstrate the effect of what this thesis refers to as pathological NBFM/LFN is given. The setup is given in table 25. The data is given in table 26.

Table 20. Central Limit Theorem Data1

$B_{IF} = 100$ kHz			
100 kS/s			
Measurement	TNQ	X^2	σ^2
1	4.6105	310.92	.0051
2	4.4903	368.01	.0043
3	4.3797	383.74	.0044
4	4.6399	317.52	.0043
5	4.4613	322.02	.0045

Table 21. Central Limit Theorem Data2

$B_{IF} = 80$ kHz			
50 kS/s			
Measurement	TNQ	X^2	σ^2
1	6.48	118.5	.0045
2	5.7222	157.8	.0044
3	6.7302	120.12	.0043
4	6.6219	218.36	.0046
5	5.5456	181.06	.0045

Table 22. Central Limit Theorem Data3

$B_{IF} = 60$ kHz			
50 kS/s			
Measurement	TNQ	X^2	σ^2
1	6.9657	213.43	.0050
2	6.159	259.1	.0051
3	7.2307	176.97	.0050
4	6.9312	188.48	.0052
5	6.77	230.46	.0053

Table 23. Central Limit Theorem Data4

$B_{IF} = 40$ kHz			
25 kS/s			
Measurement	TNQ	X^2	σ^2
1	7.1563	207.28	.0051
2	7.5309	174.86	.0048
3	7.5407	283.12	.0049
4	7.6361	189.49	.0048
5	9.4794	260.49	.0050

Table 24. Central Limit Theorem Data5

B_{IF} = 20 kHz			
10 kS/s			
Measurement	TNQ	X^2	σ^2
1	7.3942	430.3	.0051
2	6.9990	370.31	.0052
3	7.2660	364.42	.0053
4	6.2341	461.85	.0052
5	6.5395	386.61	.0050

Table 25. Settings to Demonstrate Pathological NBFM/LFN

Program Used	
File Name:	tnq.m
Comment:	1 Meg of Samples
Noise Generator Settings	
RMS Amplitude	B_m
3.6 Vrms	15 kHz
FM Modulator Settings	
Peak Dev. Switch	Δf_p
variable	variable
IF Filter Settings	
f_{lo}	f_{hi}
60	110 kHz
Oscilloscope Settings	
Sampling Rate	Volts/Division
25 KS/s	10 mV

Table 26. Pathological NBFM/LFN Data

1Meg of Samples Used		
Measurement	TNQ	Δf_p
1	4.424	300 kHz
2	4.1825	250 kHz
3	4.6207	200 kHz
4	5.5046	150 kHz
5	9.9080	105 kHz
6	8.0981	100 kHz
7	6.312	90 kHz
8	5.67	80 kHz
9	4.4051	75 kHz
10	2.883	50 kHz

Table 27. Operational Jammer Data1

$B_{IF} = 100$ kHz	
Measurement	TNQ
1	7.8605
2	7.8488
3	1.1369
4	10.2844
5	6.837

Table 28. Operational Jammer Data2

$B_{IF} = 950$ kHz	
Measurement	TNQ
1	4.4335
2	.9473
3	5.848
4	5.5916
5	.4031

B.3 Operational Jammer

In this section is recorded the TNQ measurements made on the operational jammer using the HP5411D oscilloscope. The setup was exactly as explained in Chapter 5 with a 30 MHz barrage at 6.22 GHz being mixed down to either 20 or 60 MHz and passed through an IF filter.

When the IF filter was chosen to be .1 MHz, the TNQ measured was as given in table 27. When the IF filter was chosen to be .95 MHz, the TNQ measured was as given in table 28. Note the wide variance in the noise quality measured. The appearance of the noise on the oscilloscope and spectrum analyzer changed visibly while the noise quality changed, even though the parameters of the circuit were held constant.

B.4 Final Notes on Data

More data was taken but most of it seemed redundant after the thesis was largely completed and certain conclusions were drawn based on both theoretical considerations and certain observations made after the experiments were performed, and therefore is not included in this appendix.

This data which was taken but which is not reported here may be obtained by contacting the author.

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Vita

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13. ABSTRACT (Maximum 200 words)

This thesis provides a description of FM-by-noise jamming, both at RF and at the output of the radar receiver, in terms of spectra, time-domain waveforms, and univariate probability density of amplitude. Particular emphasis is given to the case where the peak frequency deviation of the FM modulator is sufficiently small that Woodward's Theorem does not provide a good approximation of the RF spectrum. Additionally, noise quality measures which have been used to measure noise quality of radar jammers are considered theoretically and experimentally, and it is concluded that a noise measure which incorporates both a spectral measure and a probability density measure should be adopted. One such measure is proposed here. Lastly, a technique for measuring the noise quality of an operational jammer is demonstrated and the programs necessary to measure noise quality of an operational jammer are included here.

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